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Global bioenergy potentials from agricultural land in 2050: Sensitivity to climate change, diets and yields

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ABSTRACT

There is a growing recognition that the interrelations between agriculture, food, bioenergy, and climate change have to be better understood in order to derive more realistic estimates of future bioenergy potentials. This article estimates global bioenergy potentials in the year 2050, following a "food first" approach. It presents integrated food, livestock, agriculture, and bioenergy scenarios for the year 2050 based on a consistent representation of FAO projections of future agricultural development in a global biomass balance model. The model discerns 11 regions, 10 crop aggregates, 2 livestock aggregates, and 10 food aggregates. It incorporates detailed accounts of land use, global net primary production (NPP) and its human appropriation as well as socioeconomic biomass flow balances for the year 2000 that are modified according to a set of scenario assumptions to derive the biomass potential for 2050. We calculate the amount of biomass required to feed humans and livestock, considering losses between biomass supply and provision of final products. Based on this biomass balance as well as on global land-use data, we evaluate the potential to grow bioenergy crops and estimate the residue potentials from cropland (forestry is outside the scope of this study). We assess the sensitivity of the biomass potential to assumptions on diets, agricultural yields, cropland expansion and climate change. We use the dynamic global vegetation model LPJmL to evaluate possible impacts of changes in temperature, precipitation, and elevated CO_2 on agricultural yields. We find that the gross (primary) bioenergy potential ranges from 64 to 161 EJ y^{-1}, depending on climate impact, yields and diet, while the dependency on cropland expansion is weak. We conclude that food requirements for a growing world population, in particular feed required for livestock, strongly influence bioenergy potentials, and that integrated approaches are needed to optimize food and bioenergy supply.

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1. Introduction

The surging demand of a growing and increasingly affluent world population for food, fibre, and energy is confronting the earth's terrestrial ecosystems with mounting pressures. Already today, land use is degrading the ability of ecosystems to deliver vital services to humanity [1]. Changes in the global land system are a pervasive driver of global environmental change [2,3]. Land-use change often leads to biodiversity loss, changes in runoff, buffering capacities of ecosystems, greenhouse gas (GHG) emissions, soil and ecosystem degradation, and other adverse effects [4]. Moreover, climate change is confronting ecosystems globally with the challenge of adapting to changes in precipitation and temperature [5], while the effects of changes in atmospheric composition, in particular increased CO_2 concentration, are currently only incompletely understood [6,7]. Climate change may in particular affect agro-ecosystems and is currently thought to have positive as well as negative effects on yields in different regions of the world [8].

The use of biomass for energy production as a substitute for fossil energy is often seen as an attractive option to reduce fossil-fuel dependency and help reduce greenhouse gas (GHG) emissions [9,10]. It has been argued that biomass combustion with consequent carbon capture and storage (CCS) on a grand scale [11–13] might be an important option to achieve negative GHG emissions required to limit global warming to 2°Celsius until 2100, a goal thought to be required to reduce the risk of catastrophic runaway events as the earth system could reach certain "tipping points" [14,15]. The question of the magnitude and spatial patterns of global bioenergy potentials has therefore gained increased urgency in the last years [16–21].

Discussions about whether US and European biofuel policies contributed to surging prices of agricultural products and food in 2007 and 2008 [22,23] have drawn attention to another issue: A better understanding of the interrelations between the supply of food, fibre, and bioenergy is required in order to derive better-informed estimates of global bioenergy potentials and to forge strategies of bioenergy utilization that avoid unintended consequences such as strong increases in food prices or environmental pressures [24–26]. Existing studies of global bioenergy potentials did so far not, or not sufficiently, consider interrelations between food and bioenergy [10,19,27–29].

The interrelations between food and bioenergy depend on a host of factors, including economic factors (e.g., prices and trade), agricultural technology (e.g., crop yields, conversion efficiencies), changes in demand (e.g., diets, population numbers), as well as patterns and trajectories of global land use. This article aims to presents a first step towards the analysis of this complex system from the perspective of global socioeconomic metabolism. Studies of socioeconomic metabolism analyze the biophysical (e.g., material, energy) flows associated with human activities [30–34]. This approach is based on thermodynamic principles (first and second law of thermodynamics) that allow constructing mass balances for many economic activities which complement monetary economic accounts (e.g., the System of National Accounts). Material flow analysis (MFA) can be linked with inventories of ecological material and energy flows, in particular of biomass flows, through an approach that has been called the "human appropriation of net primary production" or HANPP [35–37]. Net primary production (NPP) denotes the amount of biomass produced by green plants through photosynthesis. HANPP records changes in the biomass balance of terrestrial ecosystems resulting from (1) human-induced changes in NPP, denoted as ΔNPP_{LC} (NPP change resulting from land conversion) and (2) human harvest of biomass, including biomass destroyed during harvest (NPP harvested or NPP_h) [38].

Here, we use the socioeconomic metabolism approach to develop a biomass balance model to consistently link supply and demand of agricultural biomass (forestry is excluded). The model is based on a complex, data-rich representation of global supply and demand of biomass in the year 2000. We then use the model to establish a consistent biomass balance for the year 2050 based on FAO projections [39]. All biomass flows are traced from production (agriculture and grasslands) to consumption via conversion processes, in particular those related to livestock. By comparing the production potential on cropland identified by the FAO, and the production potential of grazing lands based on calculations of their primary productivity, with the biomass demand resulting from projected global food and fibre consumption, we calculate potentials to produce bioenergy on the cropland area as projected by FAO for 2050 as well as on additional cropland that could be established on grazing areas. In estimating the latter, we explicitly considered biomass demand of livestock to be satisfied from grazing land according to the projected final demand in 2050. As the model calculates mass balances for agricultural activities, it also provides data to estimate the bioenergy potential from agricultural biomass residues. We also use the biomass model to evaluate the consequences of possible effects of climate change on crop yields – as assessed by the dynamic global vegetation model LPJmL [40] – on biomass supply and bioenergy potentials.

2. Materials and methods

2.1. *Definition of study regions and biomass aggregates*

The regional grouping underlying this study was based on the classification of the macro-geographical (continental) regions and geographical sub-regions as defined by the United Nations Statistical Division [41]. The 11 world regions are defined in Table S1 in the supplementary online material and characterized in Table 1. Population density varies considerably between the study regions, which is important because land availability has strong effects on land-use systems [42]. Whether a region is a net exporter or net importer of land-based products is determined by population density rather than development status [43]. Fertilizer use and livestock density are indicators of land-use intensity and differ strongly with population density as well as with per-capita income (see Table 1). The percentage of the total land area in each region used as cropland or grazing area is also indicative of land-use intensity and shows considerable differences among world regions.

Table 1 – Description of the study regions in terms of area, population density and land use.

	Population	Territory	Popul. density	Per-capita GDP	Livestock density	Fertilizer use	Cropland	Grazing land
Unit	[million]	[1000 km^2]	[cap km^{-2}]	[US$ cap^{-1} y^{-1}][a]	[LU/ha][b]	[kg ha^{-1} y^{-1}][c]	[%][d]	[%][d]
Source	[99]	[99]	[99]	[100]	[99]	[99]	[48]	[48]
N. Africa & W. Asia	311	10,381	29.9	2753	2.43	73.3	7%	17%
Sub-Saharan Africa	650	24,291	26.8	594	2.19	10.8	7%	49%
Central Asia & Russ. Fed.	287	22,251	12.9	1762	0.89	18.7	10%	33%
E. Asia	1481	11,762	125.9	3377	4.57	229.0	14%	45%
S. Asia	1424	6787	209.8	585	9.30	98.5	35%	41%
S.-E. Asia	518	4494	115.3	935	3.15	90.8	21%	30%
N. America	314	19,600	16.0	27 818	2.00	94.8	12%	25%
Latin America, Carribean	517	20,563	25.2	2930	4.39	73.0	8%	39%
W. Europe	389	3711	104.8	23,325	6.84	185.2	24%	31%
E. & S.-E. Europe	125	1201	104.3	2401	4.47	72.3	41%	23%
Oceania & Australia	30	8559	3.5	17,223	1.56	57.7	6%	42%
World	6046	133,602	45.3	4665	3.33	88.8	12%	36%

a Constant 1990 US$.
b Livestock units (LU) per hectare of agricultural area.
c Kilograms of pure nitrogen (kg N) per hectare of cropland and year.
d Per cent of total land area.

We used the following aggregates when working with biomass production and consumption flows. We distinguished 11 food aggregates (cereals; roots and tubers; sugar crops; pulses; oil crops; vegetables and fruits; meat of ruminants (grazers); milk, butter and other dairy products; meat of pigs, poultry, and eggs; fish; other crops). We defined seven food crop aggregates (cereals; oil-bearing crops; sugar crops; pulses; roots and tubers; vegetables and fruits; others). We distinguished two groups of livestock: all animals capable of digesting roughage were aggregated into the "grazers" group (cattle, sheep, goats, etc.). All other animals (above all pigs and poultry) were included in the "non-grazers" group. Data reported in fresh weight or air-dry weight were converted into dry matter using specific data on water content according to standard tables of food and feed composition [44–47].

2.2. *Data on land use and global biomass flows in the year 2000*

Our analysis is based on a global database for the year 2000 that consistently integrates global land-use and socioeconomic data with NPP data across a range of spatial scales, from the grid level to the country level (~160 countries). Most of these data are available over the internet (http://www.uni-klu.ac.at/socec/inhalt/1088.htm). The data have been discussed extensively in previous papers [38,48,49]; here we only provide a brief overview. The main strength of the database is that it covers three large domains of data that were cross-checked against one another and are consistent between scales (grid- and country-level) and domains (NPP, biomass harvest, by-products, livestock, biomass processing and use). The three main accounts are:

- A geographically explicit (5′ geographic resolution, i.e. approximately 10 × 10 km at the equator) land-use dataset [48]. Cropland area and forest area are consistent with FAO data on cropland [50] and the forest resource assessments FRA and TBFRA [50,51] on the country level.
- A geographically explicit (5′ geographic resolution) assessment of global HANPP [38]. The database includes, for each grid cell, NPP_0 (NPP of potential vegetation), NPP_{act} (NPP of the currently prevailing vegetation), and NPP_h (biomass harvested by humans, grazed by their livestock or destroyed during harvest or by human-induced fires [52]).
- A country-level assessment of socioeconomic biomass use that traces biomass flows from harvest to final consumption [49], based on FAO statistics. Flows not covered in statistics (e.g., grazing of livestock) were estimated based on country-level feed balances of all major livestock species. Livestock feed balances were cross-checked against the NPP of grazing areas [38]. Biomass harvest from cropland and permanent cultures, including primary crops, used and unused crop residues was calculated from the FAO agricultural production database [50].

Land-use data for the year 2000 are presented in Table 2. This dataset was cross-checked against statistical data and data derived from remote sensing [48]. 75.5% of the earth's land (excluding Greenland and Antarctica) is under human use which, however, ranges from very intensive to very extensive use. Approximately 1% of the land is used as infrastructure and urban area, 11.7% as cropland, 26.8% as forestry land, 36.0% as grazing land. Note that all land not classified as urban, cropland, forestry or unused land is included in the "grazing land" class, i.e. the land-use classes included in Table 2 cover the earth's entire land area. Grazing land is characterized by four quality classes (1–4, with 1 denoting the best grazing land and 4 the worst; for definitions see [48]). Land denoted as "grazing land" in our dataset therefore includes a large variety of ecosystem types: It comprises intensively cultivated meadows as well as barely productive semi-natural landscapes that often have

Table 2 – Land use in the 11 study regions in the year 2000. Data source [48].

	Infra-structure	Cropland	Forestry	Grazing land [1000 km^2]	Non-productive land	Unused productive land	Total[a]
N. Africa and W. Asia	42	763	268	1738	7421	47	10,279
Sub-Saharan Africa	111	1781	5828	11,867	3443	945	23,975
Central Asia and Russian Fed.	189	1572	7155	6742	280	4494	20,432
E. Asia	140	1604	2121	5146	2075	448	11,533
S. Asia	113	2305	850	2554	824	024	6670
S.-E. Asia	039	931	2098	1331	0	83	4483
N. America	337	2240	4741	4473	1549	5169	18,508
Latin America & the Carribean	64	1685	8733	7932	256	1624	20,295
W. Europe	198	862	1318	1130	11	136	3655
E. & S.-E. Europe	103	941	630	482	0	2	2158
Oceania and Australia	23	540	1216	3484	305	2817	8385
World	1360	15,225	34,958	46,881	16,163	15,788	130,375

a The total refers to territorial surface area without inland water bodies.

a very high ecological value and may be used very extensively. Of the remaining 24.5%, about one half is completely unproductive, often covered by rocks and snow or deserts with an aboveground NPP below 20 g C m^{-2} y^{-1} ("non-productive land" in Table 2). The other half ("unused productive land") includes pristine forests (c.6 Mm^2; 1 $Mm^2 = 10^6$ m $\times$ 10^6 m $= 10^{12}$ $m^2 = 1$ million square kilometers; 6 Mm^2 are approximately 4.6% of the earth's land area excluding Greenland and Antarctica), including tropical rainforests as well as all other forests with (almost) no signs of human use [53] (most of the latter in boreal regions). This category also includes rather unproductive ecosystems such as arctic or alpine tundra and grasslands.

2.3. *Matching supply and demand: the biomass balance model*

The biomass balance model (for reference see [54]) allows to calculate scenarios of the supply and demand of biomass in 2050, based on a consistent set of assumptions discussed in section 2.4. The databases described in section 2.2 were used to construct a model of biomass flows in the year 2000 in which the demand for final products is matched with gross agricultural production and land-use data (Fig. 1). We used factors derived from data for 2000 to characterize the conversion of biomass from primary harvest to final products (food and fibre), in particular through the livestock system. The model consists of two process pathways, a food crop path for the demand for cereals, roots and tubers, sugar crops, pulses, oil crops, vegetables and fruits, and other crops, and also for the demand for pig meat, poultry, eggs, and fish from aquaculture ("non-grazers"), and a roughage path for the demand for products derived from grazers (meat, milk, butter, and other dairy products).

In the food crop path, the regional demand for final biomass products (e.g. flour, vegetable oils, refined sugar) is converted to the amount of gross primary crop demand (i.e., primary products such as cereals, oil crops, sugar crops, etc.). Using global factors derived from the databases described in section 2.2, the by-products accruing from the production of final products (e.g. brans in flour production from cereals, oil-cakes in vegetable oil production from oil-bearing crops), seed requirements and the losses in the agricultural system are calculated (Fig. 1). Non-grazers (pigs, poultry) are dealt with in the food crop path as well, because they are fed (mainly) from primary or secondary cropland products. For the demand for final products (i.e. meat from pigs and poultry, eggs, and fish from aquaculture), the market feed requirement (e.g., brans, oil cakes, cereals) is calculated by applying regional input-output ratios of the monogastric livestock systems [49,55]. The resulting amount of market feed demand of non-grazers is added to the market feed demand of grazers calculated in the roughage path (see next paragraph), resulting in total regional market feed demand. This is then balanced with the regional supply of market feed from food processing and industrial processing of cereals, oil-bearing crops, and sugar crops; i.e., the supply of brans, oil-cakes, molasse, and bagasse. Usage factors for these categories were derived from the 2000 database and used to calculate the amount of market feed fed to animals. From the difference between market feed demand and the amount of by-products from processing fed to animals, the additional demand for feed grain (cereals) is calculated and added to the regional demand for cereals, taking seed demand and losses into account.

The roughage pathway refers to the demand for ruminant meat and milk, i.e. to the grazing livestock system. The grazing livestock system is characterized by a demand for market feed and a demand for non-market feed (roughage demand; i.e., the sum of fodder, crop residues fed to grazers, and grazing). The amount of feed demand per unit of output (meat or milk) varies between world regions by factors of up to 10, due to the differences in animal husbandry systems [49]. These factors depend particularly on the regional share of subsistence livestock systems (with high input-output ratios for roughage and low input-output ratios for market feed) and industrial meat and milk production (with the opposite patterns and a much higher overall efficiency due to the higher nutritional value of market feed and a production system optimized for high outputs). We calculated the regional production of ruminant meat and milk (and subsequently regional feed demand) as a function of regional roughage supply. Crop residue flows and

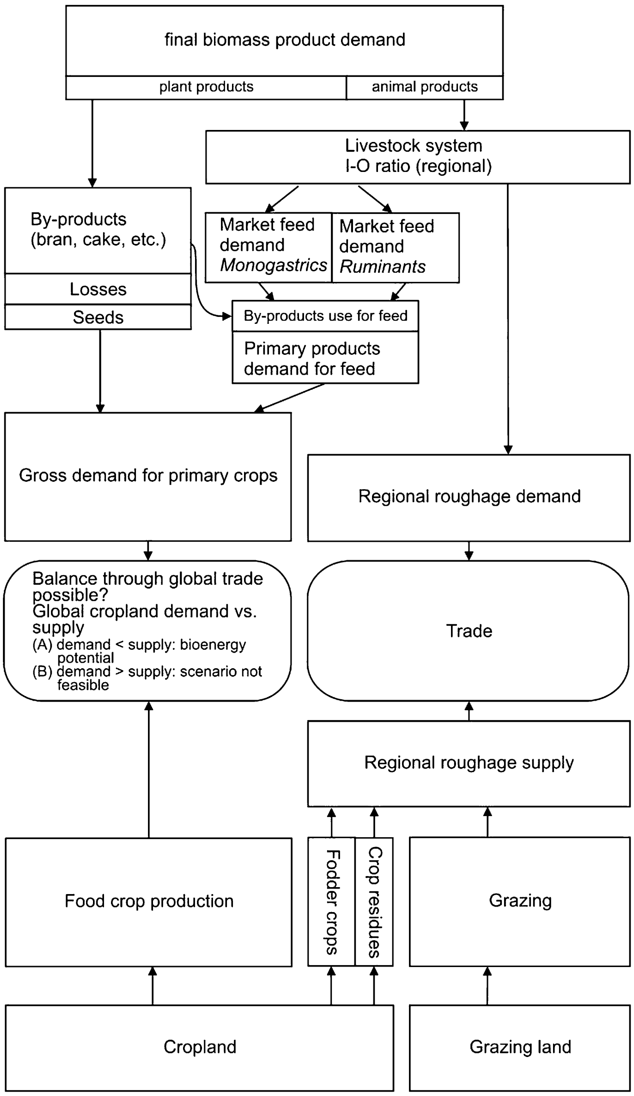

Fig. 1 – Flow chart of the biomass-balance model used to integrate supply and demand of biomass. For reference see [54].

the fractions used as feed were derived from the databases for 2000 using data on harvest indices (the ratio of grain to total plant biomass) and the usage of harvest residues as well as data on the fraction of available crop residues used for feed [38,49,56]. Fodder supply is given in FAO statistics and was converted to dry matter using standard tables, as described in section 2.1. The amount of grazed biomass was calculated from grazing land statistics [48], the actual NPP of grazing systems, and grazing intensity, i.e. the ratio of grazed biomass and actual NPP in a region [38]. The amount of total regional roughage supply was used to calculate the amount of ruminant meat and milk production in each region based on the input-output ratio of the livestock systems. From regional ruminant meat and milk production, the regional market feed demand of ruminants was derived and added to the total market feed demand.

The gap between regional supply and demand in 2000, for meat as well as for cropland products, was assumed to be balanced by international trade: for example, regions where the demand for primary products (e.g., cereals) exceeded regional supply were assumed to import; regions, where biomass supply was larger than regional demand were assumed to export. Overall, the level of uncertainty of the biomass flow model is at a satisfactory level: extrapolated global demand for gross primary crops is at 98% of the 2000 cropland production, and modelled grazing is at 99% of the grazing amount from the HANPP assessment in the year 2000 [38]. Discrepancies result from the usage of global average factors. In order to use the model to calculate bioenergy potentials for the year 2050, we modified the original model for the year 2000 as described in section 2.4.

2.4. *Assumptions for changes until 2050 compared to 2000*

With respect to population growth, we used the UN medium variant in which world population is forecast to be 9.16 billion in 2050 [57]. Total food demand was derived from forecast population numbers assuming "business-as-usual" changes in regional diets which we derived as follows. For the year 2000 we used data on food supply as compiled by the FAO [58], averaged over the period 1999–2001 in order to avoid climate or other fluctuations, and aggregated to the food categories described in section 2.1. By 2050, every region was projected to attain the diet level of the country which was "richest" (in terms of food intake) in 2000 in the respective region. The composition of the richest country's diet was adapted to the regional pattern in order to maintain appropriate fractions (for instance for pork meat in the Islamic countries of North Africa and Western Asia). The diet projected for 2050 is compared to that of 2000 in Table 3. This business-as-usual (BAU) scenario is quite similar to the business-as-usual demand growth scenarios of the FAO for 2050 [39], despite the difference in methodology [59].

In order to test the sensitivity of the bioenergy potential in 2050 to diets, we performed an alternative model run, assuming a global food supply of 11.72 MJ cap^{-1} d^{-1} (i.e. the current global average) with only 7–10% of the calorific energy animal products (see Table 3). While this "fair and frugal" diet was designed to be nutritionally sufficient in terms of calorie and protein supply, it would require equitable distribution of food in order to avoid malnutrition and imply a quite significant reduction in terms of calorie supply as well as consumption of animal products in some parts of the world. It is included here to demonstrate the dependency of bioenergy potentials on future changes in diets.

We used the UN population forecast [57] to derive an estimate of the additional area needed for urban areas and infrastructure as follows. We assumed that rural infrastructure areas are mostly driven by the need to transport agricultural inputs and produce and by the need to house agricultural population and machinery. We therefore calculated the area of rural infrastructure as a percentage of cropland area in each region, using factors derived from prior work [48]. Urban areas are much smaller than rural infrastructure. We estimated urban areas in 2050 by assuming that the per-capita amount of urban area would stay constant from 2000 to 2050. Globally, urban population is forecast to increase from

Table 3 – Food supply in 2000 and two assumptions for the year 2050: A "business-as-usual" forecast (BAU) as well as a "fair and frugal" diet ("fair") assuming a switch to equitable food distribution and less meat consumption. Absolute numbers are kilocalories per capita per day [MJ cap^{-1} d^{-1}].

	Total food supply 2000	Share of animal products 2000	Total food BAU 2050	Change in total, BAU 2050/2000 [MJ cap^{-1} d^{-1}] or per cent [%]	Share animal products BAU	Total food "fair" 2050	Change in total, "fair" 2050/2000	Share animal products "fair"
N. Africa and W. Asia	12.38	10%	13.37	8%	12%	11.72	−5%	8%
Sub-Saharan Africa	9.41	7%	11.73	25%	8%	11.72	25%	8%
Central Asia, Russ. Fed.	11.66	22%	12.87	10%	23%	11.72	1%	8%
E. Asia	12.29	19%	13.16	7%	21%	11.72	−5%	8%
S. Asia	10.15	9%	11.52	13%	13%	11.72	15%	10%
S. -E. Asia	11.21	8%	11.98	7%	11%	11.72	5%	8%
N. America	15.69	27%	15.70	0%	27%	11.72	−25%	7%
Latin America, Carrib.	11.87	20%	12.82	8%	21%	11.72	−1%	8%
W. Europe	14.36	31%	14.75	3%	32%	11.72	−18%	7%
E. & S.-E. Europe	12.86	25%	13.62	6%	27%	11.72	−9%	9%
Oceania and Australia	12.63	28%	13.46	7%	29%	11.72	−7%	7%
World	11.67	16%	12.53	7%	16%	11.72	0%	8%

2.84 to 6.37 billion [57]. For East and South-East Europe, the UN forecasts a shrinking urban population; in this region we kept the urban areas constant. We are aware that such simple assumptions can only serve to derive first-order approximations that might be too low; that is, the results are likely to be conservative. According to our calculation, urban areas grow from 279,180 km^2 to 532,880 km^2. This is not much when compared with existing cropland areas (Table 2), so the ensuing errors introduced by our estimation method will also be small.

We used FAO forecasts [39,60] to derive estimates for cropland area change and crop yields until 2050 (for reference see [54]). The FAO provides projections of crop production and its drivers (yields, area, cropping intensity) for selected important food crops (cereals, oil crops, sugar crops) for industrialized countries and five regional groups of developing countries [39,60]. FAO projections are not based on a formal model, but use expert judgements, mostly of FAO in-house experts, to derive estimates of demand for food, feed, non-food uses, seeds and wastes as well as regionally specific projections of yields and cropped areas. Balances between supply and demand are closed using so-called "supply-utilization accounts" (SUA's). The projections have to fulfil consistency criteria and are improved in an iterative process that involves several stages of revision, ensuring that sectoral and regional knowledge can be incorporated [60].

When these were available, we applied annual growth rates of crop production and its drivers (area, yield, cropping intensity) as reported by the FAO to our data [48,49] to derive total production volumes and area changes for crops and regions explicitly covered in the relevant reports [39,60] (yields were cross-checked, and slightly modified, using GAEZ data [61]). In order to avoid complications arising from working with "harvest yields" (i.e., yields per harvest event; areas with multicropping are counted each time they are harvested, fallow is omitted), we use the concept of "land-use yields" (derived by dividing the total amount of crops produced per unit of cropland area, including fallow). Land-use yields are calculated by multiplying harvest yields and cropping intensity; i.e., the number of harvests per year. Results are shown in Fig. 2. The FAO does not report projections for fodder crop production. To fill this gap, we assumed that the share of fodder crops to the overall area of arable land remains constant and that the yields of fodder crops grow with the same rate as the aggregate "other crops".

The results are plausible compared with current crop yields at the national scale [50] and alternative yield forecasts [62]. Our assumptions deviate from FAO projections only marginally, especially when compared to the level of uncertainty in such a projection. Overall, we assumed that cropland area will grow by 9% (Table 4) and yields by 54% (Fig. 2). Our assumptions are in line with other studies: IIASA scenarios suggest that global cropland area will grow by +6% in scenario B1, +9% in Scenario B2 and +12% in scenario A1 until 2050 (http://www.iiasa.ac.at/Research/GGI/). Most global agricultural scenarios assume that growth in agricultural production will depend mostly on increases of yields and only to a smaller extent on a growth of cropland areas [63,64].

In order to test the sensitivity of our calculations to assumptions on yields and cropland expansion, we also ran the model with the following assumptions: According to the scenario report of the "Millennium Ecosystem Assessment" (MEA) [1], the "TechnoGarden" scenario is comparable with FAO forecasts. The highest and the lowest yield scenarios in MEA span a range of +9% to −19% around that scenario; we used this range for our sensitivity analysis. With respect to cropland area, we also ran a scenario in which growth of cropland area was doubled in all regions and held constant in all regions where FAO forecasts shrinking cropland areas. In this expansion scenario, cropland area is assumed to grow by +19% until 2050 compared to the year 2000 (Table 4).

As this study focuses on agriculture and excludes forestry, we made the conservative assumption that growth in cropland and urban/infrastructure area reduces the area of grazing lands only, while forest areas remain constant. We assumed that the area expansion of cropland and infrastructure consumes the best grazing areas, i.e. that of class 1 and in regions where sufficient grazing land of that quality class is available, and class 2 where this is not the case (i.e. North Africa and Western Asia). The biomass-balance model calculates grazing intensity on grazing land (i.e. the ratio of biomass grazed to NPP_{act} on grazing

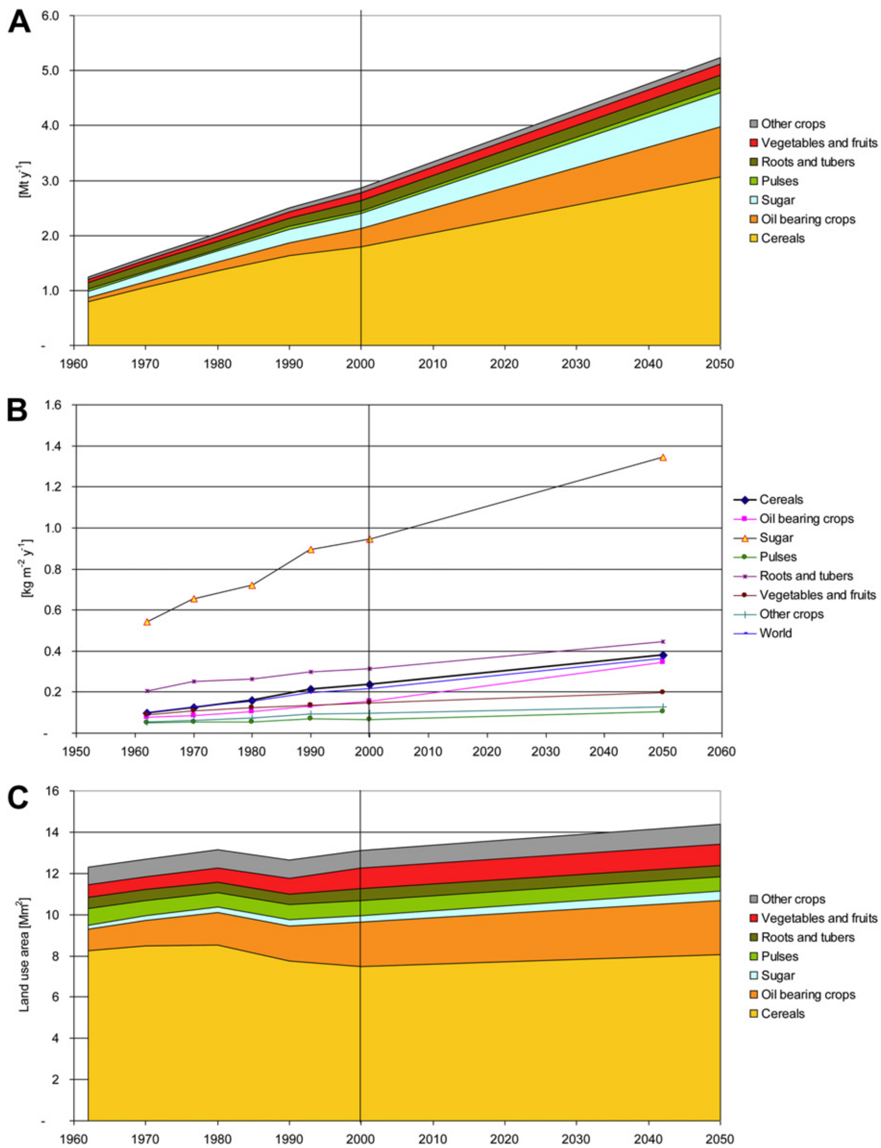

Fig. 2 – Cropland production scenario until 2050. Trajectory of (A) production, (B) land-use yields (= harvest yield times cropping intensity) and (C) cropland area 1960–2050 of food crops, break-down to major crop groups. Material flow data are reported in metric tons of dry-matter biomass. For sources and details, see text.

land) as discussed in section 2.2 (the allocation to grazing land quality classes is described in [38]). Our pattern of cropland expansion (Table 3) is comparable to other studies on global cropland potentials [65] and cropland suitability maps [66].

Based on statistical data reported by the FAO and standardized according to methods described elsewhere [49], we derived trajectories of the input-output ratios of livestock for the time period from 1961 to 2000 at the regional level which we projected until 2050 based on data on feeding efficiencies of different livestock rearing systems (see [54]). These input-output ratios reflect an assumed reduction of the respective regional subsistence fractions by 50% in favour of industrial, indoor-housed, or extensive, market-oriented production systems, depending on area availability (Table 1). Data for 1961–2000 and our projection for 2050 are shown in Fig. 3.

2.5. *Calculation of bioenergy potentials*

We calculated bioenergy potentials by distinguishing three fundamentally different production pathways: (1) bioenergy crops on cropland, (2) bioenergy crops on other lands (i.e. grazing land according to the land-use dataset used in this study), and (3) residue potentials on cropland. We calculated gross potentials for bioenergy supply by assuming that the entire aboveground NPP of bioenergy crops can be used to produce bioenergy, assuming a gross calorific value of dry-matter biomass of 18.5 MJ kg^{-1} [67]. The calculation did not take conversion or production losses into account.

In order to calculate the area available for producing bioenergy on cropland, we subtracted the area required for food, feed, and fibre calculated with the biomass-balance model

Table 4 – Cropland areas and changes in 2000 and 2050, according to our recalculation of the FAO scenario "World agriculture towards 2030/50" (FAO/BAU) and an alternative "massive expansion" assumption.

	Cropland in the year 2000	Cropland in 2050 FAO/BAU		Cropland in year 2050 massive expansion	
	[1000 km^2]	[1000 km^2]	[change]	[1000 km^2]	[change]
Northern Africa and Western Asia	763	819	+7.2%	874	+14.5%
Sub-Saharan Africa	1781	2283	+28.2%	2785	+56.3%
Central Asia and Russian Federation	1572	1635	+4.0%	1699	+8.1%
Eastern Asia	1604	1694	+5.7%	1785	+11.3%
Southern Asia	2305	2428	+5.3%	2550	+10.6%
South-Eastern Asia	931	930	−0.1%	931	0.0%
Northern America	2240	2335	+4.3%	2430	+8.5%
Latin America & the Carribean	1685	2037	+20.9%	2388	+41.7%
Western Europe	862	880	+2.1%	899	+4.2%
Eastern & South-Eastern Europe	941	890	−5.4%	941	0.0%
Oceania and Australia	540	696	+28.8%	851	+57.7%
World	15,225	16,627	+9.2%	18,134	+19.1%

described in section 2.3 in each region from each region's cropland area (section 2.4). We calculated the bioenergy potential by assuming that the NPP of bioenergy crops is equal to potential NPP [68,69] and that the entire aboveground biomass can be harvested and used to produce bioenergy. Data on potential NPP (NPP_0) were taken from previous work [38].

To calculate the potential to grow bioenergy crops on other land (i.e. grazing areas, see section 2.2), we assume that grazing land in the quality class 1 is also suitable for producing of bioenergy crops such as switchgrass (*Panicum virgatum*), *Miscanthus* sp, short-rotation coppice or similar bioenergy crops. This seems justified as a cross-check of the regional distribution of grazing areas in quality class 1 with the regional distribution of cropland potentials/suitability [65,66] revealed that regions with large cropland potentials also have large areas of high-quality grazing land and vice versa. We assume that grazing on land in grazing quality class 1 can be intensified, assuming an increase of the exploitation rate of NPP_{act} to a maximum of 67% in developing and 75% in industrialized regions. This allows using a significant fraction of the area in grazing land of quality class 1 for bioenergy crops without reducing regional roughage supply. On the area that becomes available for bioenergy crops through intensification, the bioenergy potential is estimated to be equal to aboveground NPP_{act} (taken from [38]); that is, we assume that bioenergy crops produce the same amount of aboveground biomass per year as the current vegetation [69,68].

The energy potential from unused residues on cropland was calculated by applying harvest indices and usage factors described in section 2.3. Crop residues are used as feed and for bedding. The bedding requirement was estimated by calculating the amount of manure produced by livestock and applying factors to estimate bedding demand from indoor manure production derived from [49]. We assumed that 50% of the remaining residues are required to maintain soil fertility and are therefore not available to produce bioenergy [16]. We are aware that this is a crude assumption and that higher or lower shares of the residues might be required to maintain soil fertility in different regions, depending on soil and climate conditions [70].

2.6. *Modelling of climate change effects with LPJmL*

We employed the LPJmL model [40] to estimate the effects of changes in temperature, precipitation and CO_2 fertilization on yields of major crops globally at a spatial resolution of $0.5° \times 0.5°$. Yield calculations were based on process-based simulations of 11 agricultural crops in a mechanistic coupled plant growth and water-balance model (for reference, see [40]).

We calculated percent changes in agricultural productivity between two 10-year periods: 1996–2005 and 2046–2055, representing the average productivity of the years 2000 and 2050. Management intensity was calibrated to match national yield levels as reported by FAO statistics for the 1990s [71]. National and regional agricultural productivities were based on calorie- and area-weighted mean crop productivity of wheat, rice, maize, millet, field pea, sugar beet, sweet potato, soybean, groundnut, sunflower, and rapeseed. LPJmL simulations were used only to estimate the possible magnitude of the climate-change effect on agricultural yields. In these simulations we assumed constant management intensities and cropping patterns as of the year 2000. Changes in management, breeding and cropping area were covered by other data and assumptions as described in sections 2.3 and 2.4. We did not consider feedbacks between climate change, CO_2 fertilization, and management. Still, our results provide a sound estimate of possible impacts of climate change on agricultural yields with and without CO_2 fertilization effects.

We assumed three different emission scenarios from the Special Report on Emission Scenarios (SRES): A1b, A2, B1 [72]. Each emission scenario was implemented in five different general circulation models (GCMs): CCSM3 [73], ECHAM5 [74], ECHO-G [75], GFDL [76], and HadCM3 [77]. Climate data for these GCM-projections were generated by downscaling the change rates of monthly mean temperatures and monthly precipitation to 0.5° resolution by bi-linear interpolation and superimposing these monthly climate anomalies (absolute for temperature, relative for precipitation and cloudiness) on the 1961–1990 average of the observed climate [78,79]. Since there is no information about the number of wet days in the future, we kept these constant after 2003 at the 30-year average of 1971–2000.

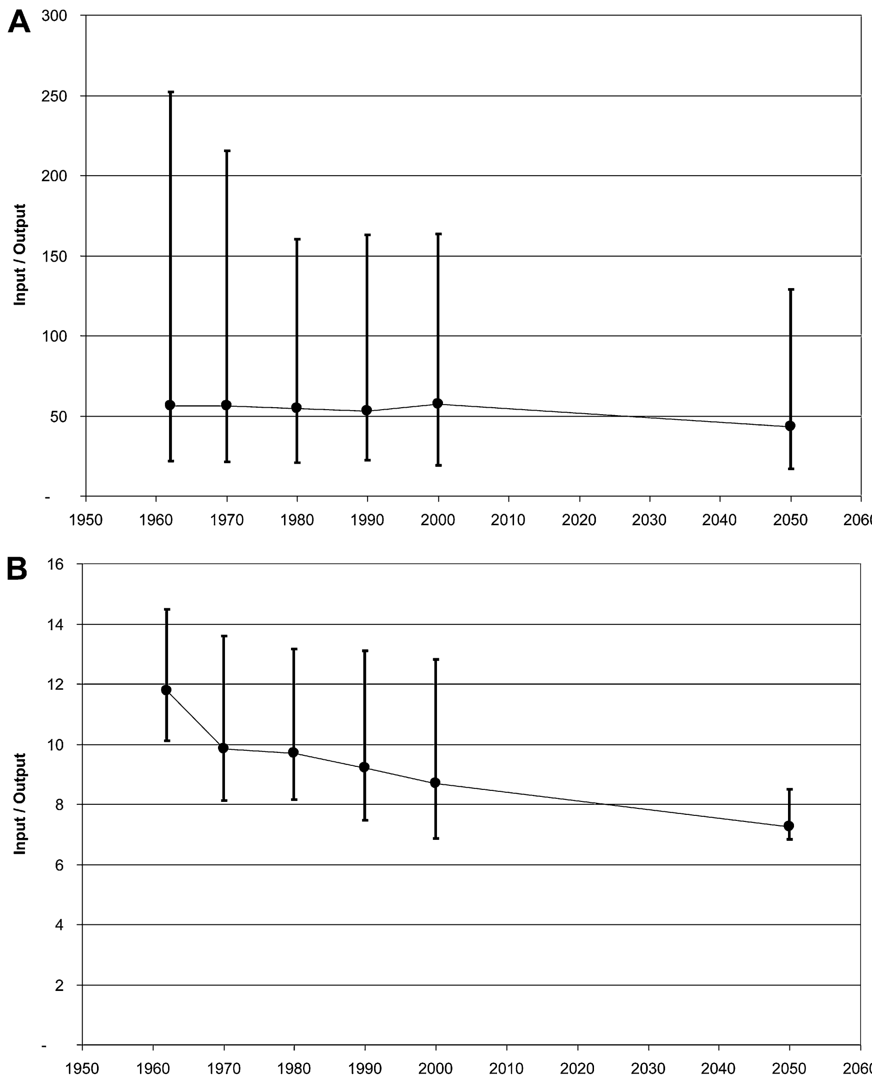

Fig. 3 – Development of livestock input-output ratios 1962–2050. Feed demand of A) Grazers (cattle and buffalo, sheep, goats), B) Non-grazers (pigs, poultry). These input-output ratios refer to the overall regional feed demand of the entire livestock population in each region ("top down"). Dots indicate the weighted global average, whiskers the ranges between regions. For details, see text.

Considerable uncertainty exists how CO_2 fertilization might influence future crop yields. This is due to both modelling uncertainties and to the fact that it seems likely that there are interrelations between management (e.g., nutrient and water availability) and the CO_2 fertilization effect. To assess the range of CO_2 fertilization uncertainty [6,7], each of the 15 scenarios was calculated twice: first, taking into account full CO_2 fertilization effects according to the prescribed SRES atmospheric CO_2 concentrations, and second, keeping atmospheric CO_2 concentrations constant at 370 ppm after 2000. In the latter case, yield changes are only driven by the modelled changes in precipitation and temperature (and the limited adaptation of management as described below), whereas in the first case the full effect of changes in temperature, precipitation, and atmospheric CO_2 levels is taken into account. Relative management levels were kept static, but sowing dates were assumed to be adapted to climate change as described by [40] and for wheat, maize, sunflower, and rapeseed (but not for all other crops) we also assumed adaptation in selecting suitable varieties.

Yield data were originally calculated at a spatial resolution of $0.5° \times 0.5°$ and then aggregated to country-level change rates. We then calculated the arithmetic mean of the change rates in all 15 scenarios with and without CO_2 fertilization effect. These country-level results were then used to calculate the area-weighted average deviation of the crop yields in each region from the yield levels projected by the FAO.

3. Results

Our estimates of changes in crop yields resulting from climate change are presented as region-specific percent change rates in Table 5. We found that crop yields increase (compared to

Table 5 – Modeled climate impact on cropland yields in 2050 with and without CO_2 fertilization.

	Mean yield change under climate change 2050	
	with CO_2 fertilization	without CO_2 fertilization
Northern Africa and Western Asia	+ 4.44%	−8.65%
Sub-Saharan Africa	+8.46%	−6.17%
Central Asia and Russian Federation	+24.91%	+5.12%
Eastern Asia	+11.96%	−3.90%
Southern Asia	+18.45%	−15.61%
South-Eastern Asia	+28.22%	−15.83%
Northern America	+12.45%	−6.25%
Latin America & the Carribean	+12.39%	−7.02%
Western Europe	+16.42%	+ 2.04%
Eastern & South-Eastern Europe	+19.08%	−0.66%
Oceania and Australia	+0.74%	−16.02%

the BAU scenario) in all 11 regions if full CO_2 fertilization is assumed, but the growth varies considerably between regions from +0.74% to +28.22% (area-weighted average: +14.76%). If the CO_2 fertilization effect is switched off, however, we find considerable losses (compared to the BAU scenario) of up to −16.02% in most regions, although some regions might still benefit (up to +5.12%); the average (area-weighted) loss of cropland yields was −7.06%.

The calculated global bioenergy potential in the absence of climate change ("business-as-usual" or BAU) is reported in Table 6. We found that the global aggregate primary bioenergy potential in the year 2050 without climate change amounts to 104.7 EJ y^{-1}. More than half of that potential comes from primary crops on other (grazing) land, i.e. from the intensification of land use on the best available grazing areas. Residues and primary crops on cropland assumed to exist in 2050 according to FAO projections (see Table 4) contribute less than 50%. Almost half of the potential comes from only two regions, namely Sub-Saharan Africa and Latin America and the Caribbean. Two other regions, Northern America and South-Eastern Asia contribute another quarter, whereas the other regions are only minor contributors.

Climate change could result in changes in cropland yields (Table 5) and in the productivity of grazing areas that would have a considerable effect on the modeled bioenergy potential, as shown in Fig. 4a: If the CO_2 fertilization effect, as modeled by LPJmL, is fully effective, the bioenergy potential might rise by up to 45% to 151.7 EJ y^{-1}, whereas it would decrease by 1690 to 87.5 EJ y^{-1} if CO_2 fertilization is assumed to be completely ineffective. Fig. 4b shows that this is only partly a result of increased yields on areas used for growing bioenergy: Growth in yields compared to BAU makes more area available for growing bioenergy, while any reduction in cropland yields results in less area availability. This implies that the global bioenergy potential on cropland and grazing areas is highly dependent on the (uncertain) effect of climate change on future global yields on agricultural areas. We found that the potential of primary bioenergy on cropland is most sensitive to climate change, whereas the potential on grazing areas and the residue potential is less affected by climate change. Note, however, that the distinction between primary bioenergy crops on cropland and grazing land is to some extent arbitrary in the sense that assuming a larger extension of cropland until 2050 increases the potential for primary bioenergy crops on cropland at the expense of the potential for primary bioenergy crops on grazing land, under *ceteris paribus* conditions (see below).

Fig. 4 also shows that the higher growth in cropland areas assumed in the "massive expansion" variant would have a small effect on the bioenergy potential (which would rise by about 6% to 110.5 EJ y^{-1} compared to BAU). The reason is the following: Cropland expansion would allow to produce more bioenergy on cropland, but less bioenergy on grazing land, as the expansion of cropland would reduce the area of grazing land and therefore the potential to grow bioenergy there without jeopardizing feed demand.

A switch to a "fair and frugal" diet would have a major impact on the bioenergy potential, however, which might be as high as 160.8 EJ y^{-1} (+54%) under these conditions. If we assume higher yields (and a BAU diet), the bioenergy potential rises to 121.6 EJ y^{-1} (+16%). If yields were to be 19% lower than assumed in the FAO/BAU scenario, it would not be possible to produce enough biomass for the BAU diet. We therefore

Table 6 – Modeled bioenergy potentials in the "business-as-usual" (BAU) scenario in the year 2050 (excluding climate change).

	Primary crops on cropland [EJ y^{-1}]	Residues on cropland [EJ y^{-1}]	Primary crops on grazing land [EJ y^{-1}]	Total [EJ y^{-1}]
Northern Africa and Western Asia	0.02	1.08	0.00	1.11
Sub-Saharan Africa	0.75	2.19	20.50	23.44
Central Asia and Russian Federation	0.88	1.08	5.95	7.91
Eastern Asia	0.48	5.06	1.30	6.83
Southern Asia	0.65	2.29	0.00	2.94
South-Eastern Asia	1.94	2.75	6.43	11.11
Northern America	5.91	5.97	3.67	15.55
Latin America & the Carribean	4.91	2.39	16.69	23.99
Western Europe	0.34	2.57	0.67	3.59
Eastern & South-Eastern Europe	1.85	1.91	2.58	6.34
Oceania and Australia	0.24	0.35	1.30	1.89
World	17.97	27.63	59.10	104.70

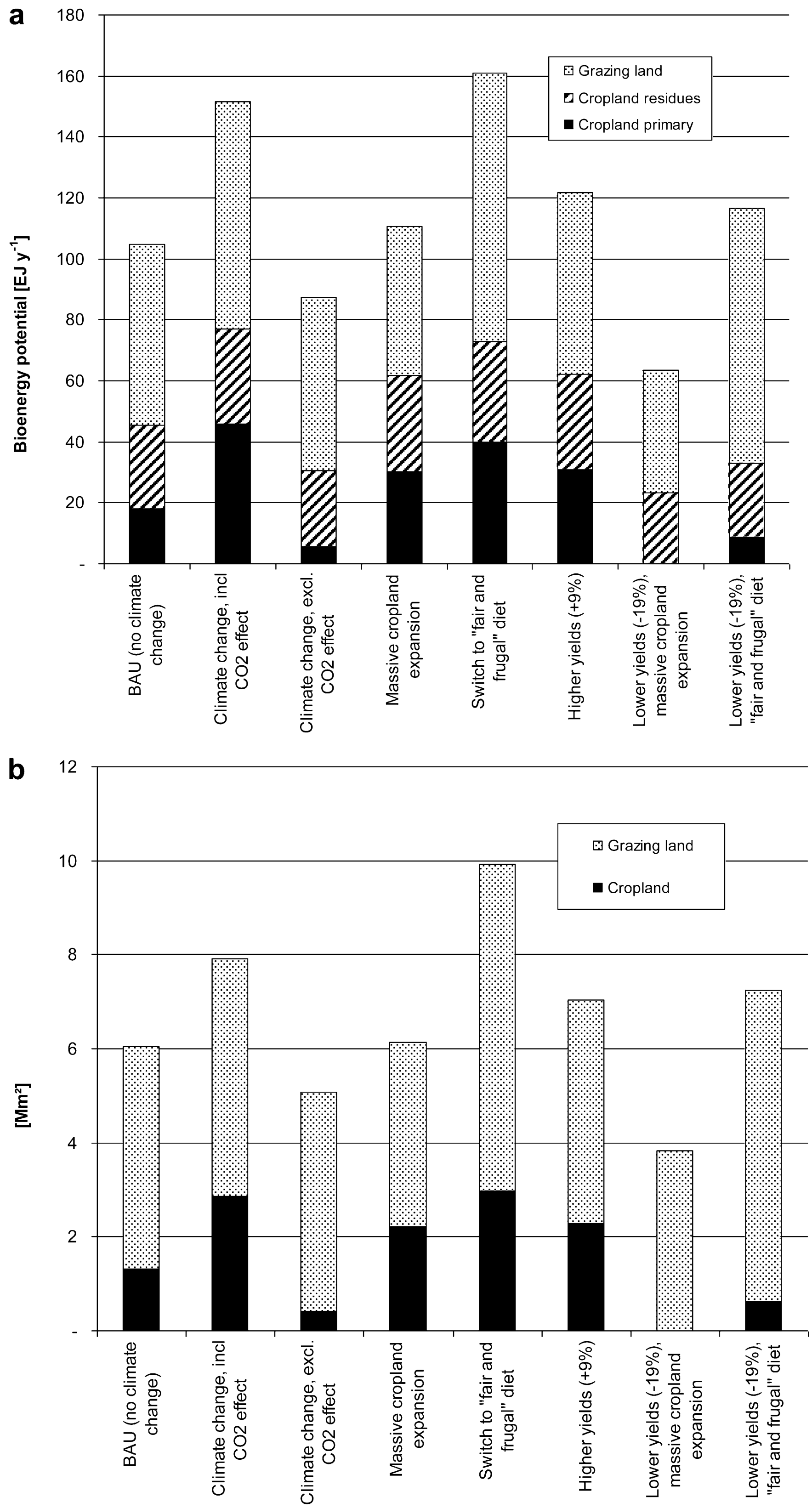

Fig. 4 – Comparison of the bioenergy potential and area used in the "business-as-usual" (BAU) scenario compared to variants in which one or two parameters were modified (all other assumptions are identical to BAU). (a) Bioenergy potential from cropland, residues and grazing land; (b) area used to grow plants designated for bioenergy use: Cropland areas and grazing areas converted to bioenergy plantations.

modelled two alternative scenarios, one that combines lower yields with a massive expansion of croplands, and one that combines lower yields with a "fair and frugal" diet. In the first case, the available cropland area is just about sufficient to produce enough food, so bioenergy could in that case only be derived from residues and grazing areas, and the potential drops to 63.6 EJ y^{-1} (−39%). In the second case, the bioenergy potential is even higher than under BAU conditions and amounts to 116.5 EJ y^{-1} (+11%).

4. Discussion and conclusions

4.1. *How realistic is the FAO forecast underlying this study?*

The results of this study are based on the FAO projections which describe a world of improved food supply and rapid agricultural intensification. Overall production on cropland increases by 68% (dry matter); maximum increases are forecast for Sub-saharan Africa (+154%) and for Latin America (+121%). In these regions, the FAO also assumes a considerable expansion of cropland, in line with studies of cropland potentials/suitability [65,66]. Note, however, that such area potential studies have been criticized [80] and that it might be difficult to cultivate the soils prevailing in these regions with currently prevailing technologies [64,81].

The largest part of the growth in total production is due to growing yields, which were assumed to increase by 54% on average for all cropland. In particular, in Western Europe and North America, cropland yields reach very high levels. It is difficult to judge whether such yield gains can be realized. It has been argued that in some regions, most options to achieve yield gains have already been implemented and yields are therefore approaching physiological limits, that the best agricultural lands are already in use and area expansions may result in the use of less well-suited land, and that soil erosion and depletion of nutrient stocks in soils may pose challenges for future yield growth [82–84]. However, improved management could help to sustain yield growth; e.g., due to improved stress tolerance, avoidance of nutrient and water shortages, or improvements in pest control. Substantial investments will be indispensable for maintaining growth in crop yields [85]. Lower rates of yield growth would result in a lower bioenergy potential, as shown in Fig. 4, while higher yields would help to increase the bioenergy potential. Achieving high yield gains might, however, result in substantial detrimental environmental impacts such as soil degradation, air and water pollution, biodiversity loss and others [64]. Judging what amount of agricultural intensification might be justified in order to increase the bioenergy potential is a complex issue that is beyond the scope of this article. Answers to this question will, among others, also depend on future development in agricultural technology [64].

Our alternative diet scenario has also shown that changes in diets compared to often-expected trajectories (growth in calorie supply and more animal products) might result in considerably higher bioenergy potentials. It should be noted, however, that the "fair and frugal" diet modelled here might be considered to be near to the lower boundary of the possibility space for that parameter, while food demand might also be thought to grow more strongly than modelled here (or by the FAO), as the global average 2050 in the BAU scenario is well below levels of food and animal product supply enjoyed today in regions such as the US and Western Europe [54] (see Table 3).

4.2. *Uncertainties regarding climate change impacts*

The climate change effect on crop yields is highly uncertain. Depending on climate scenario (not shown) and the assumptions on the effectiveness of CO_2 fertilization, most regions may experience significant decreases in crop yields as well as significant increases. The most important factor is the uncertainty in CO_2 fertilization which was explicitly analyzed here. This effect can, in principle, increase crop yields considerably due to enhanced carbon assimilation rates as well as improved water-use efficiency. Whether or not farmers will be able to attain increased crop yields under elevated atmospheric CO_2 concentrations will depend on the availability of additional inputs, especially nitrogen [86]. Increased carbon assimilation rates can only be converted into productive plant tissue or the harvested storage organs if sufficient nutrients are available to sustain additional growth. Where plant growth is constrained by nutrient limitations, additional growth is limited. On top of that, there is some likelihood that the quality of agricultural products decreases under increased CO_2 fertilization, as e.g. the protein content diminishes [87]. There is also evidence that crops grown under elevated CO_2 concentrations might be more susceptible to insect pests [88].

A positive climate-change effect on crop yields may be expected in regions currently constrained by too low temperatures, as in the northern high latitudes and in mountainous regions. Here, all 30 model runs uniformly indicate increases in crop yields by 2050. By contrast, there is hardly any location where all model runs uniformly indicate decreases in crop yields if CO_2 fertilization is assumed to occur. If the CO_2 fertilization is switched off, however, many regions, especially tropical croplands are uniformly projected to experience decreases in crop yields in all 15 climate scenarios. It has to be noted that the beneficial effects of CO_2 fertilization are subject to heavy debate [6,7]. Results presented here only indicate the order of magnitude of climate-related impacts on crop yields. Besides uncertainties in future development of drivers (climate change, CO_2 fertilization effect, management, technological change), modelling of crop yields at large scales adds to the overall uncertainty as many processes are necessarily implemented only in a simplified manner. If farmers have access to a broad selection of crop varieties, they are likely to select varieties most suited for the local growing conditions, which could not be fully considered here.

4.3. *Interpretation of bioenergy potential calculations*

When interpreting the calculated bioenergy potentials it is essential to keep in mind that these are gross potentials for bioenergy supply; that is, the gross calorific value (GCV) of the entire aboveground plant material assumed to be available for as feedstock for bioenergy production (section 2.5). If one assumes that the plant material is directly used for combustion for heat or combined heat and power (CHP) without much (or any) conversion, this is a reasonable approximation of the primary energy available. The production of liquid biofuels with current (first-generation) technologies, however, can only convert parts of the plants into fuels and entails substantial losses due to the conversion process. On the other hand, first-generation biofuel production would also deliver feed which is not considered in our biomass balances. A considerable fraction of the bioenergy potential calculated here would not be suitable for this utilization pathway, for example the residue potential and an unknown part of the potential on grazing areas. Even in areas where first-generation biofuel production would be possible, the energy potential would be significantly (50–75%) lower due to losses [16,68,69]. Second-generation technologies for the production of liquid biofuels would be capable of using a considerably larger fraction of the plant materials available for bioenergy production, but would also involve conversion losses. A recent assessment recommends to favour direct use of solid plant materials over conversion to liquids, primarily based on comparisons of the GHG balances of different technologies [16].

Our assumption to base our estimates of bioenergy potentials on current (grazing areas) or potential (cropland) NPP (section 2.5; other recent studies [68,69] used similar assumptions) is also a simplification that might result in over- or underestimation of the potential. At present, the actual aboveground NPP on cropland and grazing areas is considerably lower than the potential NPP of these areas in the global average [38]. However, it would probably be possible to raise the NPP of bioenergy crops above the potential NPP of the areas on which they are planted through irrigation, fertilization, and other agricultural technologies, at least in many regions. While this might increase the amount of plant material produced, it would probably also result in a deterioration of the energy return on investment (EROI) and could lead to reduced, if not negative net energy gains [89,90]. Economic (agricultural investments) as well as biophysical (soil degradation, water availability) factors might also limit yield gains [64,85,91]. We conclude that our bioenergy potential estimates could be regarded as a realistic to conservative: while we assume increases over current productivity levels, we do not assume massive intensification.

4.4. *Comparison with other assessments of bioenergy potentials*

Our bioenergy potential calculations do not include bioenergy potentials from forests. In the year 2000, the amount of wood fuels harvested in forests had an energy value of approximately 22 EJ [50]. The IEA reports that the total amount of "primary solid biomass" used for energy production globally was 39.4 EJ [92,93]. No comprehensive data exist to identify how much of the bioenergy currently used by humans comes from forests, from wastes in production processes, and from cropland and grazing areas. The potentials identified in this study include the unknown amount of bioenergy produced

Table 7 – Current and projected future level of global biomass and energy use and global terrestrial net primary production: A compilation of estimates.

	Energy flow [EJ y^{-1}]	Year	Sources
1. Current global NPP and its use by humans (gross calorific value)			
Total NPP of plants on earth's land	2191	2000	[38]
Aboveground NPP of plants on earth's land	1241	2000	[38]
Human harvest of NPP including by-flows, total	346	2000	[38,49]
Human harvest of NPP including by-flows, aboveground	310	2000	[38,49]
NPP harvested and actually used by humans	225	2000	[38,49]
2. Global human technical energy use (physical energy content)			
Fossil fuels (coal, oil, natural gas), gross calorific value	453	2008	[101] [a]
Nuclear heat (assumed efficiency of nuclear plants 33%)	30	2008	[101]
Hydropower (assumed efficiency 100%)	11	2008	[101]
Wind, solar and tidal energy (100% efficiency)	1	2006	[102]
Geothermal (10% efficiency for electricity, 50% for heat)	2	2006	[102]
Biomass, including biogenic wastes, gross calorific value	54	2006	[102] [b]
Total (physical energy content, gross calorific value)	551	2006–2008	[101,102]
3. Estimates of global bioenergy potentials or scenarios 2050 (calorific value not standardized)			
Bioenergy crops and residues, excluding forestry, this study	64–161	2050	
Mid-term potential according to the World Energy Assessment	94–280	2050	[10]
Review of mid-term potentials according to Berndes et al.	35–450	2050	[27]
Mid-term potential according to Fischer/Schrattenholzer	370–450	2050	[103]
Potential according to Hoogwijk	33–1135	2050	[104]
IPCC-SRES scenarios mid-term	52–193	2050	[72]
Bioenergy potential on abandoned farmland	27–41	2050	[69,68]
Bioenergy potentials in forests	0–71	2050	[18]
Surplus agricultural land (not needed for food & feed)	215–1272	2050	[19]
Bioenergy crops (second generation)	34–120	2050	[16]

a BP reports energy data in tons of oil equivalent (toe) net calorific value (NCV). We assumed that 1 toe = 41.868 GJ (NCV). Conversion from NCV to gross calorific value (GCV) was based on the following multipliers (GCV/NCV): coal 1.1, oil 1.06, natural gas 1.11 [105].
b The IEA reports biomass as NCV; we converted this to GCV using a multiplier of 1.1.

currently on cropland and grazing areas. The potential to produce bioenergy from forests was recently quantified to range from zero to 71 EJ y^{-1} in the year 2050: the global technical potential for forest bioenergy in 2050 was found to be 64 EJ y^{-1}, the economic potential 15 EJ y^{-1}, the ecological potential 8 EJ y^{-1} and the combined economic-ecological 0 EJ y^{-1} [18].

Table 7 compares the results of this study on global bioenergy potentials with current global biomass flows, with the current level of energy use, and with other studies on global bioenergy potentials. It shows that humans currently harvest and use a total amount of biomass with an energy value (GCV) of about 225 EJ y^{-1}, and that the total amount of biomass harvested, destroyed or burned due to human activities currently is around 310 EJ y^{-1}. This is a considerable fraction of the current aboveground NPP which is approximately 1241 EJ y^{-1}. These figures indicate that the primary bioenergy potential identified in this study (64-161 EJ y^{-1}) is considerable when compared to the current levels of human harvest and use of biomass or to current aboveground NPP.

The second part of Table 7 reveals, however, that the potential contribution of bioenergy from cropland and grazing areas is only a fraction of current fossil-fuel use. As shown in the lower part of Table 7, our estimate is considerably lower than the bioenergy potentials identified in many previous studies. We note that our estimate of primary bioenergy potential on cropland and grazing land is very similar to that of the WBGU [16], despite the fact that the methodology used by the WBGU was completely different from the one used here, but significantly lower than that found in other studies that did not consider links between food, feed and bioenergy.

5. Conclusions and recommendations

We conclude that the bioenergy potential on agricultural land in 2050 is highly sensitive to climate change as well as to changes in yields and diets. More research is required to better understand feedbacks between management, changes in precipitation, temperature, and the magnitude of the CO_2 fertilization effect under field conditions, all of which have a strong effect on the bioenergy potential. Our results suggest that the magnitude of global bioenergy potentials in the year 2050 is strongly affected by the need to produce feed for livestock, and that the careful consideration of biomass flows in the food system, in particular in the livestock system, is highly important in deriving realistic potentials for future bioenergy supply. Our results suggest that the bioenergy potential on agricultural areas in 2050 might be in the order of magnitude of 100 EJ y^{-1} based on current diet trajectories and a ‘food first’ approach; if ‘poorer’ diets are chosen, the potential may rise by up to 60%. A considerable fraction of this potential comes from agricultural residues, suggesting that in-depth assessments of options to combine bioenergy production and soil fertility management (e.g., energy production through biogas production that maintains a large proportion of the nutrients and parts of the carbon) should be undertaken. An integrated optimization of food and energy production based on a “cascade utilization” of biomass is an important option to produce and use bioenergy sustainably [16,94,95]. Bioenergy potentials on grazing land, as calculated in this study, are substantial, but realizing them might entail massive investments in agricultural technology, such as irrigation infrastructure, and might be associated with vast social and ecological effects, such as a further pressure on populations that practice low-input agriculture. Realizing this potential might also trigger land-use change such as deforestation in far distant regions if not combined with robust measures to prevent such effects [17,96,97]. At least at present, growth in agricultural production is a strong driver of deforestation [98].

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Appendix. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.biombioe.2011.04.035.

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