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Dependency of global primary bioenergy crop potentials in 2050 on food systems, yields, biodiversity conservation and political stability

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HIGHLIGHTS

- ▸ Global energy crop potentials in 2050 are calculated with a biophysical biomass-balance model.
- ▸ The study is focused on dedicated energy crops, forestry and residues are excluded.
- ▸ Depending on food-system change, global energy crop potentials range from 26–141 EJ/yr.
- ▸ Exclusion of protected areas and failed states may reduce the potential up to 45%.
- ▸ The bioenergy potential may be 26% lower or 45% higher, depending on energy crop yields.

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ABSTRACT

The future bioenergy crop potential depends on (1) changes in the food system (food demand, agricultural technology), (2) political stability and investment security, (3) biodiversity conservation, (4) avoidance of long carbon payback times from deforestation, and (5) energy crop yields. Using a biophysical biomass-balance model, we analyze how these factors affect global primary bioenergy potentials in 2050. The model calculates biomass supply and demand balances for eleven world regions, eleven food categories, seven food crop types and two livestock categories, integrating agricultural forecasts and scenarios with a consistent global land use and NPP database. The TREND scenario results in a global primary bioenergy potential of 77 EJ/yr, alternative assumptions on food-system changes result in a range of 26–141 EJ/yr. Exclusion of areas for biodiversity conservation and inaccessible land in failed states reduces the bioenergy potential by up to 45%. Optimistic assumptions on future energy crop yields increase the potential by up to 48%, while pessimistic assumptions lower the potential by 26%. We conclude that the design of sustainable bioenergy crop production policies needs to resolve difficult trade-offs such as food vs. energy supply, renewable energy vs. biodiversity conservation or yield growth vs. reduction of environmental problems of intensive agriculture.

1. Introduction

The use of biomass as a source of energy used in heating systems, power and cogeneration plants or vehicle motors is forecast to grow considerably in the next decades (Nakicenovic and Swart, 2000). Bioenergy is promoted for several reasons, e.g. reducing the dependency on exhaustible fossil energy, greenhouse gas (GHG) emissions and import dependency as well as creation of jobs and income in rural areas. However, in recent years the awareness has been growing that energy crop production could have far-reaching adverse consequences if natural and socioeconomic constraints are not respected. Examples include the discussion on possible impacts of bioenergy on food prices (World Bank, 2008), ecological consequences of agricultural intensification (Tilman, 1999; Tilman et al., 2002), deforestation and high GHG emissions from land-use change (Fargione et al., 2008; Searchinger et al., 2008), soil degradation (Lal, 2006; van Vuuren et al., 2009), water demand of energy crops (Gerbens-Leenes et al., 2009a) and pressures on biodiversity (Gibbs et al., 2008). Some of these potential adverse impacts might even annihilate the environmental benefits of bioenergy (Tilman et al., 2009; Searchinger, 2010).

Forging bioenergy strategies that maximize benefits and minimize adverse effects is a formidable challenge, aggravated by a limited understanding of the magnitude and geographic distribution of future potentials, and their large uncertainties (Haberl et al., 2010). Biomass currently contributes approximately 46 EJ/yr of

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technical energy in the form of solid, liquid and gaseous fuels from primary (harvest) as well as secondary and tertiary (waste and residue utilization) sources (IEA, 2006). Recent estimates of additional future bioenergy potentials range from approximately 30 to over 1000 EJ/yr for 2050 (Beringer et al., 2011; Berndes et al., 2003; Campbell et al., 2008; Field et al., 2008; Haberl et al., 2010c; Haberl et al., 2012a; Hoogwijk et al., 2003; Hoogwijk, 2004; Smeets et al., 2007; van Vuuren et al., 2009). The enormous differences between these studies largely result from differing assumptions regarding the large number of factors that influence the availability of biomass for energy and material use, such as the availability and suitability of land, achievable yield levels of energy crops, technological progress in agriculture and livestock breeding, and on the impact of competing land uses such as the demand for food and feed, biodiversity and forest conservation and soil protection.

In this context, we here study the following factors that influence global primary energy crop potentials in 2050. First, we analyze possible constraints on the area available to grow energy crops resulting from (1) future changes in food systems, i.e. food demand (diets), food and feed crop yields, feed demand of livestock (fodder crops and roughage) depending on livestock feeding efficiency, (2) political factors, i.e. sufficient stability of nations to allow investments required for establishing bioenergy plantations (exclusion of failed states) and (3) competing area demands for biodiversity conservation (e.g. nature reserves). Our study is based on the conservative assumption that additional deforestation is excluded for both food and energy crop production in order to avoid long carbon payback times from direct and indirect land-use change (Fargione et al., 2008; Searchinger et al., 2008; Searchinger, 2010; WBGU, 2009). Second, we evaluate the influence of energy crop yields on future bioenergy potentials by assuming different plausible levels of energy crop yields. Bioenergy potentials from forestry as well as from agricultural residues, manures and other wastes, which are substantial (Haberl et al., 2010), are outside the scope of this study. This study is based on a 'food first' approach, i.e. only areas not required to feed the world population forecast to exist in 2050 according to the specified diet are assumed to be available for bioenergy.

We use a simple and transparent biophysical biomass-balance model (Erb et al., 2009a; Haberl et al., 2010; Haberl et al., 2012a) that is based on material flow accounting (MFA) principles and large, consistent land-use socioeconomic and ecological biomass-flow databases (including net primary production; Erb et al., 2007; Haberl et al., 2007; Krausmann et al., 2008). We aim at analyzing the effect of various constraints on future primary bioenergy potentials, but it is neither our objective to forecast bioenergy supply in 2050, nor to assess its social implications, e.g. economic and social effects of land competition (e.g. land rents, food and bioenergy prices or expulsion of peasants). Thus, we here aim at exploring the biophysical option space for primary bioenergy production in 2050, using food-first and zero-deforestation assumptions as framework condition of our analysis. We do not aim at assessing economic bioenergy potentials, e.g. modeling energy demand and supply in dependency of price developments, nor technical bioenergy potentials, i.e. maximum potentials related to technological capabilities.

2. Methods

The biomass-balance model is based on the thermodynamic principles underlying material and energy flow accounting (MEFA) methods, basically the conservation of mass and energy and the entropy law (Ayres and Simonis, 1994; Fischer-Kowalski, 1998; Fischer-Kowalski and Hüttler, 1998; Haberl, 2001; Haberl et al., 2004). The model has been described in detail elsewhere (Erb et al., 2009a; Erb et al., 2012; Haberl et al., 2010; Haberl et al., 2012a); here we only give a short overview and explain our assumptions.

The model calculates the global primary energy crop potential based on assumptions on diets, agricultural technology and cropland area assumed for the year 2050 (Fig. 1) and for eleven world regions (see supplementary material). The model was constructed using a comprehensive land use, NPP and biomass-flow database for the year 2000 (Erb et al., 2007; Haberl et al., 2007; Krausmann et al., 2008). The database integrates global land use and socioeconomic data with NPP data across a range of spatial scales, from the grid level (5 min resolution, ~10 × 10 km at the equator) to the country level (~160 countries). It fulfills multiple consistency criteria across scales and domains: biomass flows are traced from the net primary production (NPP) of each of the five land-use classes (built-up and infrastructure, cropland, forestry, unused and unproductive, all other land) to national-level data on primary and final biomass consumption. The database was used to derive factors and multipliers to match the demand for final products of biomass (food, fibers) with gross agricultural production and land use for eleven world regions (for reference see Haberl et al., 2012a and http://www.uni-klu.ac.at/socec/downloads/WP116_WEB.pdf). That is, in a first step, the model was calibrated for the year 2000 using the above-described databases. In a second step, several critical factors and input parameters were modified in order to reflect assumed changes from 2000 to 2050 (see below).

The biomass-balance model uses a spatially explicit land-use dataset (Erb et al., 2007; see Table 1) that distinguishes five land-use classes (1) infrastructure and urban areas, (2) cropland, (3) forestry, (4) unused areas ('wilderness', including unproductive areas), and (5) all other land (denoted as 'grazing land' in the

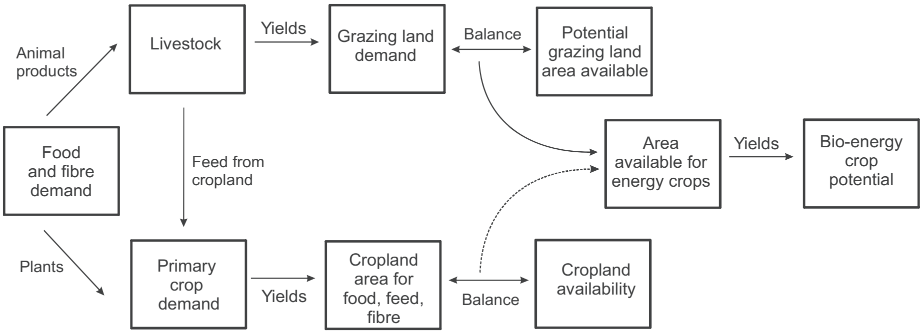

Fig. 1. Model concept of the biomass-balance model used in this study.
Source: redrawn after Haberl et al. (2010)

Table 1
Global land use in 2000 and 2050 in the TREND scenario.

	Urban land, infrastructure[a] (1000 km^2)	Change 2050/2000 (%)	Cropland incl. energy crops[a] (1000 km^2)	Change 2050/2000 (%)	All other land (incl. grazing)[a] (1000 km^2)	Change 2050/2000 (%)	Forestry (constant)[a] (1000 km^2)	Unused land (constant)[a] (1000 km^2)	Total (1000 km^2)
N. Africa & W. Asia	42	59%	763	7%	1 738	–5%	268	7 468	10 279
Sub-Saharan Africa	111	85%	1 781	120%	11 867	–19%	5 828	4 388	23 975
Central Asia & Russ. Fed.	189	4%	1 572	44%	6 742	–10%	7 155	4 774	20 432
E. Asia	140	11%	1 604	14%	5 146	–5%	2 121	2 522	11 533
S. Asia	113	60%	2 305	5%	2 554	–7%	850	848	6 670
S.-E. Asia	39	31%	931	46%	1 331	–33%	2 098	84	4 483
N. America	337	19%	2 240	20%	4 473	–11%	4 741	6 718	18 508
Latin America, Carribean	64	32%	1 685	87%	7 932	–19%	8 733	1 880	20 295
W. Europe	198	7%	862	8%	1130	–7%	1 318	147	3 655
E. & S.-E. Europe	103	0%	941	24%	482	–47%	630	2	2 158
Oceania & Australia	23	46%	540	47%	3 484	–8%	1 216	3 121	8 385
Global total	1 360	24%	15 225	40%	46 881	–14%	34 958	31 951	130 375

[a] In the year 2000.

original paper) at a resolution of 5 arc minutes (approximately 10 per 10 km at the equator). The area of class 5 ‘all other land’ was calculated by subtracting from each gridcell’s total area the area covered by all other four land-use classes. Forests were either subsumed in class 3 (forestry) or class 4 (unused land), depending on presence or absence of human artefacts as identified in the underlying ‘wilderness’ map (Sanderson et al., 2002). The land-use dataset was extensively cross-checked against independent datasets (Erb et al., 2007). Land-use class 5 includes only non-forested land used by humans, ranging from high quality meadows and grazing land to shrub-dominated or otherwise marginally productive areas that allow only extensive grazing, including also savannahs, abandoned farmland, as well as degraded and extensively used areas and semi-deserts. Furthermore, this land use class is classified according to its suitability for livestock grazing, discerning four quality classes, from 1 (best) to 4 (poorest), based on land-cover information from the GLC-2000 map (Mayaux et al., 2006) and NPP data (for reference see Erb et al., 2007).

Class 4, ‘wilderness’, occupies approximately one quarter of the global ice-free land surface (i.e. excluding Greenland and Antarctica) but holds little promise for energy crops because most of this land is extremely unproductive (e.g., arctic or alpine tundra or extreme deserts). The ‘wilderness’ class also includes pristine forests which were excluded from the here presented analysis due to very long carbon payback times associated with their use and biodiversity conservation considerations.

Areas potentially available in the year 2050 for growing energy crops are estimated as the sum of (a) cropland not required for food, feed and fiber production and infrastructure and (b) land potentials existing in the ‘all other land’ category. Infrastructure and urban areas in the year 2050 (Table 1) were extrapolated from values for 2000 based on the medium UN population forecast and urbanization trends (UN, 2007). With respect to the ‘all other land’ category, area can only be assumed to be available for energy crops if roughage demand for livestock is satisfied, according to the ‘food first’ principle (see Fig. 1). In order to estimate the area that could be made available for energy crops in 2050 on such lands, depending on roughage demand, we assumed that all ‘other land’ of the highest grazing suitability (grazing class 1) could be intensified to an extent currently observed in countries with high grazing intensity, i.e. a harvest level of up to 67% (developing countries) and 75% (industrialized countries) of aboveground NPP. We then assumed that the area set free through this assumed intensification would be available for energy crops in 2050 (additional constraints – e.g. from biodiversity conservation – are described below).

The TREND scenario for 2050 was derived based on the UN medium population forecast (UN, 2007) and FAO agricultural projections. The FAO study ‘World agriculture towards 2030/2050’, which was used here, assumes a global growth in cropland area of 9% (Table 1) and a growth of cropland yields of 54% (weighted average of all crops and regions) from the year 2000 to 2050 (Bruinsma, 2003; FAO, 2006). The TREND diet (Table 2) was constructed by assuming that each region would attain the food supply enjoyed in the country within each region that currently has the ‘richest’ diet in 2050. This procedure yielded results that were very similar to the FAO forecast (FAO, 2006), despite the different methodology (Erb et al., 2009a).

Livestock feeding efficiencies (Fig. 2) were extrapolated to 2050 separately for grazers (cattle, sheep, goats, etc.) and monogastric species (pigs, poultry, etc.) based on region-specific trends derived from FAO statistics for the year 1961–2000 (Erb et al., 2009a; Krausmann et al., 2008). This estimates were complemented by a second variant in which lower feeding efficiencies, i.e. those currently achieved in organic farming, were assumed to prevail in 2050 (see Erb et al., 2009a; Fig. 2).

In addition to the cropland scenario displayed in Table 1 we also considered a ‘massive cropland expansion’ variant in which FAO assumptions on cropland expansion in each region were doubled (and held constant in regions where the FAO forecasts a declining cropland area). This variant assumes a global growth of cropland area of 19% until 2050. This ‘massive cropland expansion’ variant is still lower than the cropland expansion assumed to occur in some other global scenario studies (IAASTD, 2009). The largest expansion of cropland areas is assumed to occur in Sub-Saharan Africa and Latin America, as these are the regions generally thought to have the largest cropland potentials (IIASA and FAO, 2000; Ramankutty et al., 2002). It was assumed that the additional cropland has a 10% lower productivity than the cropland of the TREND expansion because it would be located on less productive lands.

Table 2
Diet scenarios for 2050 compared to the situation in the year 2000.

	World average		Minimum[a]		Maximum[a]	
	Food supply (MJ/cap/d)	Animal food (%)[b]	Food supply (MJ/cap/d)	Animal food (%)[b]	Food supply (MJ/cap/d)	Animal food (%)[b]
Year 2000	11.67	16	9.41	7	15.69	31
Rich	13.28	21	12.56	19	15.07	27
TREND	12.53	16	11.52	8	15.70	32
Less meat	12.53	8	11.52	6	15.70	9
Fair & frugal	11.72	8	11.72	7	11.72	10

[a] Minimum/maximum of the per-capita value of the 11 regions.
[b] Per cent of animal food in total caloric intake.

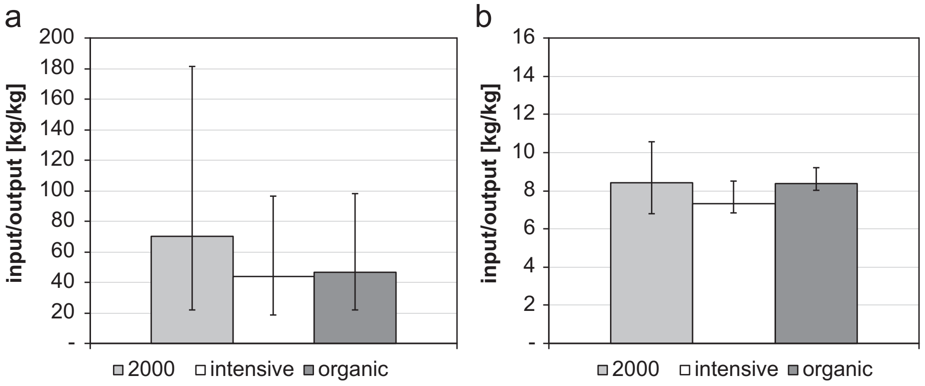

Fig. 2. Global livestock feeding efficiencies (unweighted arithmetic mean of regions) for 2000 according to Krausmann et al. (2008) and assumptions for 2050 for (a) ruminant species and (b) monogastric species. Whiskers indicate the maxima and minima of regional factors. Unit: kg dry matter/kg dry matter.Note: feeding efficiencies are defined as the ratio of the feed requirement of all livestock (including working animals and animals for reproduction) per unit output of usable animal biomass. Input and output are both measured as dry matter biomass.

We assumed that the area expansion of cropland and infrastructure would consume the areas with the highest suitability for grazing in the ‘other land’ class. This assumption seems justified as regions with much land best suited for grazing according to our land-use dataset are also those in which GAEZ (IIASA and FAO, 2000) and other studies (Ramankutty et al., 2002) indicate the existence of large potentials for cropland expansion. In contrast, regions with little cropland expansion potential according to IIASA and FAO (2000) and Ramankutty et al. (2002) also have small areas of high-quality grazing land according to the Erb et al. (2007) dataset. Land in grazing class 1 was found to be large enough to account for this change with the exception of the region ‘North Africa and Western Sahara’. In this region, cropland and infrastructure area expansion is assumed to consume land of grazing quality class 2 as well. Reduced roughage production in 2050 as a result of the ‘consumption’ of grazing areas by cropland was explicitly accounted for in the biomass-balance model in the respective regions. Grazing land expansion through forest clearance was not considered. Despite this restrictive assumption, grazing area was not found to limit roughage supply in any of the scenarios.

In order to assess the possible effect of changes in diet on the area available for energy crops, three alternative diet variants were defined (Table 2). In the ‘rich’ variant we assumed global convergence towards diets currently enjoyed in Western Europe and the USA, although these levels are not fully reached in 2050. In the ‘less meat’ variant we assumed the same level of calorie and protein supply as in the TREND scenario but with a lower level of animal-based products (milk, meat and eggs). The ‘fair and frugal’ variant results in a convergence towards a global daily per-capita calorie intake of 2 800 kcal/cap/day (11.72 MJ/cap/d), paired with a relatively low level of animal product supply. This latter diet is nutritionally sufficient (also in terms of protein supply, which is assumed to be based to a large extent on pulses and other protein-rich vegetables) but requires globally equal distribution of food in order to avoid malnutrition in parts of the global population. Conversely, even at the highest supply level malnutrition cannot be entirely ruled out if inequality in per-capita supply is assumed to remain at its current level (Erb et al., 2009a).

Table 3
Global average yields (metric tons of dry matter biomass per hectare and per year) on cropland in 2000 and in the four yield scenarios.

	2000	MAX	FAO	INT	ORG
	[t/ha/yr]				
Cereals	2.4	4.2	3.9	3.3	2.8
Oil bearing crops	1.6	3.8	3.5	3.0	2.5
Sugar crops	9.7	14.8	13.6	12.0	10.5
Pulses	0.7	1.2	1.1	1.0	0.9
Roots and tubers	3.2	5.0	4.6	4.1	3.6
Vegetables and Fruits	1.5	2.2	2.0	1.7	1.5
Other crops	1.0	1.4	1.3	1.1	1.0

In order to reflect changes in cropland yields, we defined three alternative variants regarding future cropland yields (Table 3). The maximum yield level (MAX) was defined based on the ‘Global Orchestration’ scenario in MEA (Millennium Ecosystem Assessment, 2005) which assumes yields that exceed the level forecast by the FAO in 2050 by 9%. A minimum yield level was defined by calculating crop yields in 2050 under 'wholly organic' conditions (ORG), i.e. by assuming that 100% of the cropland area would be cultivated according to standards of organic agriculture. According to a literature review (Erb et al., 2009a), yields in organic agriculture are approximately 40% lower than those of industrialized agriculture if calculated over the whole crop rotation cycle, i.e. taking fallow cycles or the cultivation of N-fixating leguminous plants into account (Halberg et al., 2006; Connor, 2008; von Fragstein und Niemsdorff and Kristiansen, 2006). This yield reduction was only applied to high-input cropland systems that mainly prevail in industrialized countries, and not to low-input agriculture. In developing countries, organic agriculture would allow further yield growth because the nutrient status of croplands is often very poor and can be improved with organic techniques (Halberg et al., 2006; Diop, 1999). Thus, the deviation of the organic yield scenario from the baseline was based on the regional mix between high-input and low-input agriculture (Table 3). The 'intermediate' (INT) yield scenario was calculated as the arithmetic mean between FAO and ORG. It may be interpreted as a scenario in which cropland agro-ecosystems are not pushed to their very limits due to environmental considerations, or as a trajectory in which yield levels forecast by the FAO are not achieved for economic (lack of investment) or biophysical (physiological limits, soil degradation, etc.) reasons.

The biomass-balance model was used to determine the feasibility of combinations of assumptions on diets (4 variants), food and fodder crop yields (4 variants), cropland expansion (2 variants) and livestock feeding efficiency (2 variants). Scenarios in which global cropland area demand exceeded global cropland availability by more than 5% were labeled as 'non-feasible' and not further considered. We considered a difference of supply and demand smaller than 5% not to be significant given the uncertainties in the biomass balance model. The matching between supply and demand was performed on the global level; regional imbalances were assumed to be equalized by trade. Roughage supply was not found to be a limiting factor, as a consequence of the large extent of global grazing areas (Erb et al., 2007) and low average grazing intensities in most regions. For all scenarios classified as 'feasible' we calculated the area available for energy crops as the sum of (a) cropland area not required for food, feed and fiber and (b) area available for energy crops on 'all other land' while covering roughage supply for livestock on smaller, but more intensively used areas (see above).

We calculated the primary bioenergy potential of energy crops for 'feasible' scenarios as follows. In the TREND scenario we assumed that aboveground biomass yields of energy crops are related to natural productivity; that is, net primary production or NPP (Field et al., 2008; Campbell et al., 2008). As we were interested only in primary energy potentials, we did not differentiate between energy crop plants or bioenergy utilization pathways (first/second generation). On croplands, we assumed biomass yields equal to the aboveground NPP of potential vegetation (i.e. the vegetation assumed to exist in the absence of land use). On all other land areas we used data on the aboveground NPP of the currently prevailing vegetation. All NPP data were taken from prior work (Haberl et al., 2007). Field et al. (2008) and Campbell et al. (2008), who used the same approach, argued that this assumption may be regarded as optimistic because cropland NPP is currently 35% lower than the potential NPP of the respective areas. This assumption implies that energy crops will achieve substantially higher yields in 2050 than those currently achieved by food crops in the global average, compared to the natural potential of the areas on which they are grown. 'First generation' biofuels are based on food crops, therefore our energy crop yield assumptions may be regarded as optimistic for most first-generation crops with the exception of sugarcane (WBGU, 2009). We therefore developed a 'low yield' variant based on the conservative assumption that energy crop yields in 2050 would only achieve a level of 65% of the potential aboveground NPP of the area on which they are planted.

However, much previous work on energy crop potentials was based on much higher yield expectations. For example, based on IMAGE, van Vuuren et al. (2009) assumed second generation energy crop yields of 1–3 kg dry matter per m^2 and year which is approximately 1.5–4.5 times larger than the potential aboveground NPP of the cropped area. Calculations with the dynamic global vegetation model LPJmL suggest that the biological productivity of second generation biofuel crops such as C4 grasses and short-rotation coppice ranges from 0.8 to 1.2 kg/m^2/yr of dry matter biomass, i.e. slightly higher than potential NPP, largely depending on the level of irrigation (WBGU, 2009; Beringer et al., 2011). In line with a recent study (Johnston et al., 2009) suggesting that yield assumptions for first generation biofuels had been largely overestimated, we did not assume high energy crop yield estimates as implemented in IMAGE (van Vuuren et al., 2009) but rather those resulting from LPmL (Beringer et al., 2011; WBGU, 2009) by assuming a 'high yield' variant in which energy crops yields were 1.3 times higher than potential aboveground NPP.

We assumed that dry-matter biomass has a gross calorific value of 18.5 MJ/kg to derive primary energy supply potentials from the biomass flow data. This calculation does not take any conversion or production losses into account. The conversion from primary biomass to final or useful energy can entail significant losses, in particular for first generation bioenergy, depending on the respective technology (Campbell et al., 2008; Field et al., 2008; WBGU, 2009), which are not deducted here. We also do not deduct direct or indirect energy inputs; e.g. energy used for cultivation,fertilizer production or processing – in other words, we report gross biomass production potentials of energy crops.

In order to consider potential constraints from biodiversity conservation, we followed an approach used in recent studies (Beringer et al., 2011; Brooks et al., 2006; WBGU, 2009) based on (a) biodiversity hotspots, (b) wilderness areas and (c) protected areas. For (a) biodiversity, we used data on biodiversity hotspots (Myers et al., 2000), endemic bird areas (Stattersfeld et al., 1998), centers of plant diversity (WWF and IUCN, 1994) and the 'global 200' dataset (Olson and Dinerstein, 2002). In order to consider (b) wilderness areas, we used biodiversity wilderness areas (Mittermeier et al., 2003), frontier forests (Bryant et al., 1997) and the 'last of the wild' wilderness area map (Sanderson et al., 2002). In addition, we (c) superimposed the protected areas with IUCN levels I and II provided by the world database on protected areas (UNEP-WCMC, 2010).

We used the number of conservation data sets for a given area as a proxy for calculating a per-cent reduction in the area availability for energy crops. We followed the approach of Beringer et al. (2011) who developed two variants. In the first, less restrictive, variant 100% of the area of each pixel was excluded only if more than one wilderness layer was present, 50% of the area if two biodiversity hotspots were present, and 80% if there were three or more. Moreover we reduced the area availability by 80% for protected areas. Each of these rules was applied separately, and the most restrictive result was implemented. For the second, more restrictive, variant we decreased the area available for energy crops by 100% if a pixel was classified as 'wilderness' by any of the wilderness datasets. All land areas, regardless of the presence of any biodiversity hotspot or protected area, suffer a 10% decrease in available energy crop area. With the presence of one (two, three, four) biodiversity hotspot(s), the share of area assumed to be available for energy crops was reduced by 20% (30%, 50%, 80%). Protected areas were excluded completely in the more restricted variant. Again, the three calculations were performed separately and the most restrictive result was used.

In order to exclude areas where investment in energy crop plantations is highly unlikely due to lack of stable legal and political framework conditions, we excluded 'failed states' (Newman, 2009) based on the list published by the Fund for Peace for the year 2010 (www.fundforpeace.org). This list ranks 177 countries by analyzing 12 primary social, economic and political indicators, each of which split into a set of sub-indicators, which are summed up to a 'failed-state' index. The 30 countries with the highest index were treated as areas without any energy crop potential due to lack of stability required for investments into energy crop plantations.

3. Results

In the TREND scenario which assumes cropland expansion and yields as forecast by the FAO, livestock efficiencies as well as diets in line with the FAO projections and ignores constraints from biodiversity conservation and unstable political framework conditions, we find a global primary energy crop potential of 77 EJ/yr. This result is based on the TREND variant of energy crop yields (the notion of 'scenario' here stands for a unique combination of variants, i.e. assumptions on the different factors discussed in the 'methods' section). Fig. 3 shows a map displaying the spatial distribution of the bioenergy production in this scenario which underlines that a considerable proportion of the total potential is located in Sub-Saharan Africa and Latin America.

Fig. 4 displays the bioenergy potential in the 43 (of a total of 64) scenarios which were classified as 'feasible', showing a large range from 26 to 141 EJ/yr from dedicated energy crops. Energy potentials shown in Fig. 4 vary according to changes in diets, cropland expansion, food and feed crop yields and feed conversion efficiencies of livestock as discussed above. They do not consider constraints from biodiversity conservation or lacking political stability and are based on the TREND assumption on energy crop yields.

Fig. 4 shows that diet has a strong effect on energy crop potentials. Energy crop potentials and diets are inversely related to each other (Fig. 4a): 'richer' diets result in lower energy crop potentials, while more frugal diets, especially those with less animal products, leave more space to plant energy crops. The interrelation between food crop yields and energy crop potentials is less straightforward, however. While there is a general tendency that energy crop potentials increase with food crop yields (Fig. 4b), variability between the highest and lowest values also increases – the highest and lowest scenario in terms of energy crop potential are both based on the MAX yield variant.

Fig. 5a shows how constraints resulting from political instability ('failed states') and exclusion of areas for biodiversity conservation affect the energy crop potential in 2050. These calculations were all based on the TREND scenario with respect to food system and energy crop yields. The exclusion of failed states reduces the global

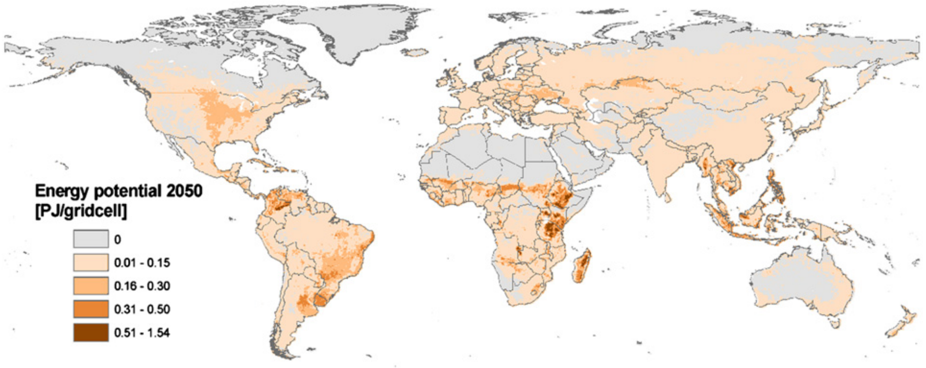

Fig. 3. Map of energy potentials in PJ per yr and gridcell, according to the TREND scenario for 2050.

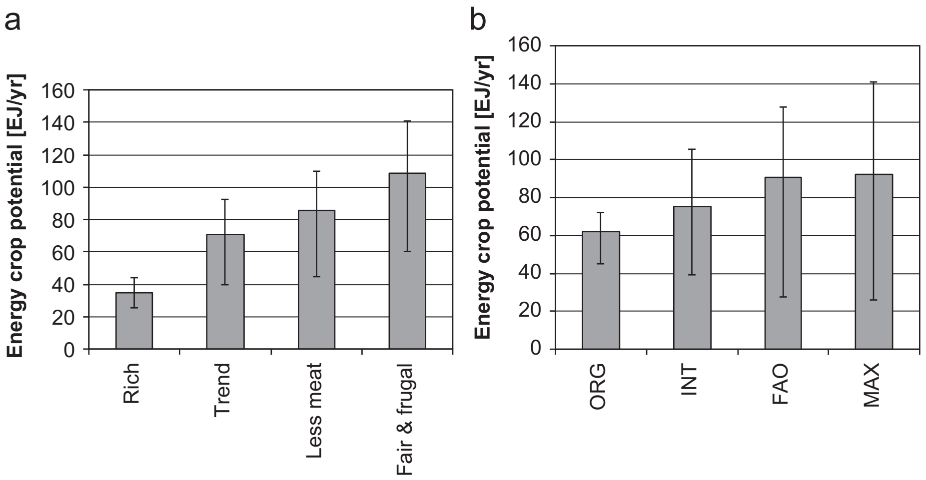

Fig. 4. Dependency of the global energy crop potential in 2050 on (a) changes in diets and (b) yields of food crops. Gray bars show the mean of all 'feasible' scenarios (i.e. all scenarios that would deliver enough food for the respective diets), whiskers the range between the lowest and the highest scenario. These calculations use the medium energy crop yields and do not consider political (failed states) and conservation-related constraints.

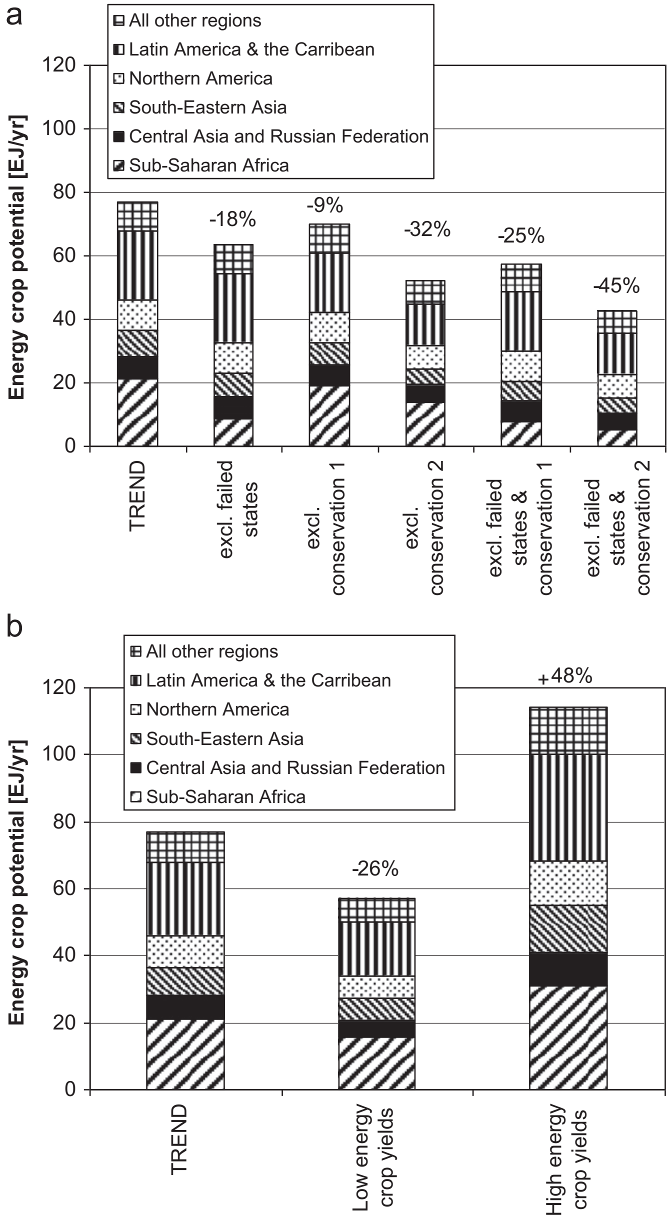

Fig. 5. Global energy crop potentials in 2050 compared to the TREND scenario (a) considering constraints from political instability (failed states) and exclusion of biodivesity conservation areas (conservation 1: low conservation; conservation 2: rigorous conservation), (b) depending on assumptions on energy crop yields: TREND vs. low respectively high energy crop yields.

energy crop potential by 18%; a large part of this reduction results from exclusion of areas in Sub-Saharan Africa. The exclusion of areas for biodiversity conservation reduces the global bioenergy potential by 9–32%, depending on the ambition of conservation efforts. The combined effect of constraints from conservation and political stability reduces the global energy crop potential by 25–45%.

Fig. 5b shows how strongly future bioenergy potentials depend on energy crop yields. The low assumption – a relation between energy crop yields and the NPP of potential vegetation on the areas planted with energy crops equal to that currently found on the world's average croplands – reduces the energy crop potential in 2050 by 26% compared to the TREND scenario, while high energy crop yields could boost the potential by up to 48% to 114 EJ/yr. Under such optimistic assumptions, yield growth could approximately compensate the losses resulting from exclusion of areas in failed states and high-biodiversity areas.

4. Discussion

In interpreting the results, it is important to bear in mind that we here calculated primary biomass supply potentials. Some conversion pathways, e.g. production of liquid biofuels, can only use parts of the plants and entail considerable conversion losses, e.g. in liquefaction. Moreover, biomass production as well as conversion to fuels requires energy inputs (Pimentel et al., 1973; WBGU, 2009). Hence, the net energy (Cleveland, 2007) delivered to society is considerably lower than the primary energy crop potentials calculated here (e.g., Blottnitz and Curran, 2007; Cleveland et al., 2006; Giampietro et al., 1997). The optimization of biomass utilization pathways in order to maximize the amount of useful energy delivered per unit of primary biomass harvested is beyond the scope of this paper, but is of course highly important in designing sustainable bioenergy strategies (e.g., see Haberl and Geissler, 2000; WBGU, 2009).

The primary energy crop potentials calculated in this study on basis of a biophysical analysis, is 77 EJ/yr in the TREND scenario, with wide ranges resulting from different assumptions on the food and agricultural system, political stability required for investment security, and biodiversity conservation, are similar to those identified with the dynamic global vegetation model LPJmL (Beringer et al., 2011; WBGU, 2009), higher than those assumed to exist on abandoned land, i.e. 27–41 EJ/yr (Campbell et al., 2008; Field et al., 2008), and considerably lower those identified in earlier studies (Hoogwijk et al., 2003; Hoogwijk, 2004; Smeets et al., 2007). Our result is similar to a recent model-based assessment (Popp et al. 2011a) which reported a global economic bioenergy potential in 2050 of approximately 70 EJ/yr if deforestation was excluded (100 EJ/yr if not) based on a combination of a plant growth model (LPJmL) with a land allocation model (MAgPIE) and an energy model (ReMIND). Another study of global bioenergy trajectories under different carbon tax systems using the MiniCAM integrated assessment model (Wise et al., 2009) found that bioenergy supply might grow to over 100 EJ/yr if only fossil-fuel based C emissions were limited, which would, however, trigger considerable deforestation. When all C emissions were limited, including those from land-use change, bioenergy supply in 2050 was much lower (below 40 EJ/yr). We excluded, by assumption, bioenergy production on deforested lands. Our results are therefore well in line with recent model-based assessments.

Assumptions on the energy crop yields that can be achieved in 2050 are among the most important reasons for the discrepancies in estimates of global bioenergy potentials. Previous modeling studies may have been overly optimistic in their assumptions on future energy crop yields. For example, Smeets et al. (2007) suggested that in 2050 up to 1272 EJ/yr of bioenergy could be produced from energy crops grown on up to 36 million km^2 (27% of the global land surface excluding Antarctica and Greenland). However, this result was based on a yield assumption that was 3.8 times higher than current NPP of these areas (Haberl et al., 2010) As discussed above, yield assumptions in past studies of energy crop potentials may have been too high (Johnston et al., 2009), although vegetation models suggest that high-yielding energy crops such as C4 grasses or short-rotation coppice can achieve yields that exceed natural productivity by perhaps 20–40% (Beringer et al., 2011; WBGU, 2009). Water supply may become an issue here, as high-yields can only be achieved if sufficient water is available (Fader et al., 2010; Gerbens-Leenes et al., 2009b; Rost et al., 2008). On the other hand, while it may be technically possible to achieve high yield levels or improve livestock feeding efficiencies to an extent that would allow to plant more area with energy crops than assumed here, the environmental and economic costs of such strategies could be substantial and need to be considered.

Our results suggest that the future global energy crop potential strongly depends on changes in the food system. Assumptions on diet have a strong effect on the area demand for food production (Stehfest et al., 2009), and thus on the energy crop potential. The 'rich' diet leaves little space for bioenergy plantations, irrespective of food and feed crop yields, while the 'fair & frugal' diet allows for large bioenergy crop potentials. As one moves from rich to poorer diets, the range between the lowest and highest potential also increases (Fig. 4a). This is a result of the fact that the 'fair & frugal' diet leaves a lot of area available for bioenergy if the most intensive technologies with respect to food and feed crop yields and feeding efficiency are adopted. However, while such a combination would allow a high level of energy crop production, it may also be perceived as being particularly unlikely. In the case of the 'fair & frugal' diet, substantial energy crop potentials exist even if 'organic' yields and low feeding efficiency are assumed.

Changes in the assumptions on food and feed crop yields also have a substantial effect on the energy crop potential: higher yield levels leave more space for energy crop plantations if everything else remains constant. However, it does not seem likely that future diets are independent on food crop yields and vice versa. Higher yields are likely to be linked with richer diets, for example because food consumption and agricultural technology are both linked to affluence: rich societies can afford to eat better, but they also acquire the means to increase their agricultural yields (Godfray et al., 2010b; Krausmann et al., 2009). In our analysis (Fig. 4b), the lowest bioenergy potential estimate found in any of the scenarios was based on high food and feed crop yields. The reason is that the 'rich' diet can only be provided with high yields. This diet variant combined with lower yields were all classified as 'not feasible' and consequently excluded. A rich diet leaves little space for energy crop plantations due to the high roughage demand for livestock, irrespective of yield levels of food crops. In other words, pushing yields to their limits also allows richer diets, which then in turn may reduce the energy crop potential if people adopt diets that include more animal products.

It is beyond the scope of this article to assess whether, and under which conditions, it is more favorable in terms of GHG emissions/uptake to use the area that becomes available due to high yields and/or more vegetarian diets for bioenergy provision instead of using it for C sequestration (Stehfest et al., 2009; Haberl et al., 2012b). Our study, however, reveals that this is not the only trade-off related to bioenergy production that requires systematic attention.

Our analysis clearly illustrates trade-offs between maximizing energy crop supply and adopting environmentally less burdensome agricultural technologies. At present, agricultural intensification results in higher yields but is often associated with substantial environmental pressures resulting from fertilizers, pesticides, machinery use, etc. Impacts of intensive agriculture include soil degradation, nitrogen leaching, risks from pesticides, among others (IAASTD, 2009; Popp et al., 2011b; Smeets et al., 2009). Everything else being equal, lower food and feed crop yields leave less space for energy crop plantations, and lower energy crop yields also result in a lower bioenergy potential. Many technologies proposed to reduce environmental pressures from agriculture, e.g. organic farming, tend to reduce yields, which mean that more area is needed to produce the same amount of food. To what extent these trade-offs can be mitigated through 'sustainable intensification' (Godfray et al., 2010a; Tilman, 1999) remains to be seen.

An additional trade-off exists between biodiversity conservation and maximization of energy crop production. Our results suggest that the exclusion of wilderness areas, protected areas and biodiversity hotspots could lower the global energy crop potential by 9–32%, depending on the ambition of conservation efforts. This calculation does not include the possibility that conservation targets could also constrain food crop production, which might indirectly result in additional restrictions for planting more energy crops. A focus on biomass residues and wastes instead of purpose-grown bioenergy plants would allow to tap into a substantial energy potential of up to 100 EJ/yr (Haberl et al., 2010) and would deliver energy without increased pressures on ecosystems resulting from additional land demand. However, use of some residues may pose a risk for the maintenance of soil fertility (Blanco-Canqui and Lal, 2009; Lal, 2006), hence secure upper limits to extraction of agricultural residues need to be respected. Where these limits are depends on soil characteristics, climate and many other region-specific factors; this is an area where more research is needed.

About one quarter of the global energy crop potential calculated for 2050 in the TREND scenario is located in countries currently classified as 'failed states'. No projection is available to what extent lacking political stability might affect global energy crop potentials in 40 years, so the share of the global potential that is inaccessible due to political constraints is at present unknown. However, our calculations support the conclusions of previous assessments (Beringer et al., 2011; WBGU, 2009) that such constraints might be substantial.

The design of sustainable bioenergy crop production policies needs to resolve intricate trade-offs between food and energy supply, renewable energy and biodiversity conservation or yield growth and reduction of environmental pressures from intensive agriculture. Our assessment indicates that policy strategies are needed that succeed in simultaneously optimizing production and consumption systems and considering the many potential conflicting uses of biomass, land and water. Increasing crop yields seems to be essential, given the growing world population, the growing energy demand in the light of global environmental changes. But such strategies will only be successful if not overcompensated by consumption surges and if sustainable methods for intensification can be developed.

Our analysis also reveals that successful policies will have to optimize the increasingly globalized, i.e. spatially separated, land use and biomass utilization chains in integrative ways (Erb et al., 2009b; Meyfroidt et al., 2010). In this context, our analysis reveals one particular intricacy: whereas the largest bioenergy demands are expected in regions where energy potentials are low such as Europe and parts of Asia, the largest energy potentials are found in regions such as Sub-Saharan Africa. These regions are characterized by poor food supply and often also by failing institutions. Expanding agricultural land use in these regions will require massive investments, which might not be affordable for local governments or land users and are not attractive for international investors if political stability is low. Moreover, sensitive legislation will be required to avoid land-use changes with negative social effects, e.g. see the current 'land grab' discussions (Friis and Reenberg, 2010; Zoomers, 2010).

By necessity, growing energy crops requires land. If substantial amounts of bioenergy should be derived from purpose-grown energy crops, the land area required needs to be significant as well. The gross energy content of all biomass harvested by humans globally for food, feed, fiber and bioenergy was approximately 230 EJ/yr in the year 2000 (Krausmann et al., 2008). This biomass was harvested on almost three quarters of the global land surface (excluding Antarctica and Greenland) through cropping, grazing and forestry (Erb et al., 2007; Haberl et al., 2007). Producing some 50–150 EJ/yr of energy crops in 2050, in addition to the growth of biomass required to adequately feed a world population of perhaps 9.1 billion, is therefore an endeavor that should not be underestimated.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.enpol.2012.04.066.

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