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The global technical potential of bio-energy in 2050 considering sustainability constraints

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Bio-energy, that is, energy produced from organic non-fossil material of biological origin, is promoted as a substitute for non-renewable (e.g., fossil) energy to reduce greenhouse gas (GHG) emissions and dependency on energy imports. At present, global bio-energy use amounts to approximately 50 EJ/yr, about 10% of humanity's primary energy supply. We here review recent literature on the amount of bio-energy that could be supplied globally in 2050, given current expectations on technology, food demand and environmental targets ('technical potential'). Recent studies span a large range of global bio-energy potentials from ≈30 to over 1000 EJ/yr. In our opinion, the high end of the range is implausible because of (1) overestimation of the area available for bio-energy crops due to insufficient consideration of constraints (e.g., area for food, feed or nature conservation) and (2) too high yield expectations resulting from extrapolation of plot-based studies to large, less productive areas. According to this review, the global technical primary bio-energy potential in 2050 is in the range of 160–270 EJ/yr if sustainability criteria are considered. The potential of bio-energy crops is at the lower end of previously published ranges, while residues from food production and forestry could provide significant amounts of energy based on an integrated

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Introduction

Biomass is energy derived from living or recently living organisms. Biogenic materials derived from agricultural crops, residues, forest products, aquatic plants, manures and wastes can be combusted either directly or after conversion processes (liquefaction, gasification, *etc.*) to produce heat, mechanical energy or electricity (bio-energy). Increased use of bio-energy is promoted in many countries as a means to reduce import dependency, use of non-renewable energy (fossil fuels) and greenhouse gas (GHG) emissions.

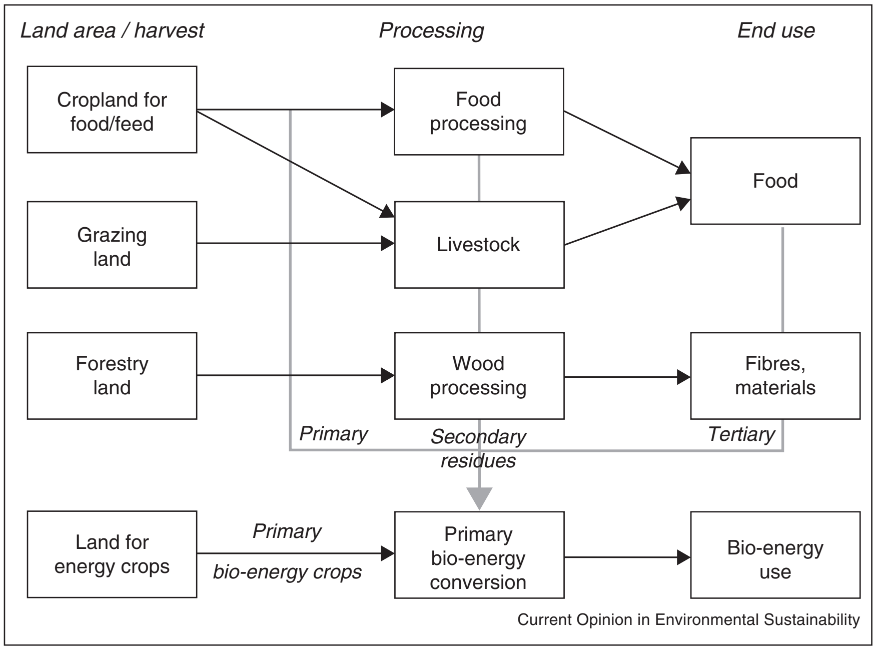
The primary process through which biomass becomes available on earth is photosynthesis: plants use solar energy to produce energy-rich organic matter from inorganic inputs (CO_2, water and nutrients). The amount of biomass produced by plant growth (i.e. net of plant respiration) is denoted as Net Primary Production (NPP). At present, the total NPP on the earth's continents is approximately 2200 EJ/yr, of which some 1240 EJ/yr are allocated to aboveground components of plants [1••]. Humans currently harvest, burn or destroy during harvest approximately 370 EJ/yr [2,3]. A large fraction of this biomass is used in the food system. Data on current global bio-energy use are uncertain. Most researchers agree on a range of 40–

creating heavy indoor pollution [4,5••,6].

Published estimates of global technical bio-energy potentials in 2050 — the year to which most mid-range projections or scenarios refer — differ by a factor of almost 50. Calculations of the potential to grow bio-energy crops on abandoned farmland yielded a range from 27 to 41 EJ/yr [7,8], while recent studies suggest total global bio-energy potentials of up to 500 EJ/yr [9,10•], some even reporting potentials exceeding 1000 EJ/yr [11]. These discrepancies primarily result from different assumptions on future yields of food and energy crops, feed conversion efficiencies in the livestock system as well as the suitability and availability of land for bio-energy production. We here aim to identify a range of future technical bio-energy potentials that take sustainability criteria such as nature conservation and food production into account. We review recent studies that considered constraints and opportunities for bio-energy production and perform own calculations in order to be able to present all data in a global breakdown to 11 regions (Table S1, *Supporting Online Material, SOM*).

We discuss three major components of the global bio-energy potential (Figure 1): (1) dedicated bio-energy

Figure 1



Land and biomass resources considered in this review.
Source: modified after [4,59].

crops, (2) agricultural residues, animal manures, and municipal solid waste (MSW) and (3) biomass (residues) from forestry. This paper only estimates the energy value of the biomass that could be available in 2050 as primary energy, that is, we do not take into account conversion losses (e.g., during liquefaction). Except where explicitly stated differently, we report biomass flows as dry matter (= bone dry biomass = oven dry = zero moisture content), assuming that 1 kg dry matter biomass is equivalent to 0.5 kg of carbon and has a gross calorific value of 18.5 MJ/kg. The potential to produce bio-energy from algae is not covered (e.g., see [12,13]).

Dedicated bio-energy crops

Most recent studies on global technical bio-energy potentials suggest that plants specifically cultivated to provide bio-energy represent the largest component of future 'modern' bio-energy production. A variety of plants can be grown for this purpose, including woody lignocellulosic crops (e.g., poplar, willow, and *Eucalyptus*), herbaceous lignocellulosic crops (e.g., switchgrass, *Miscanthus*), oil crops (e.g., rape seed, sunflower, and *Jatropha*), sugar crops (e.g., sugar cane, sugar beet), cereals (e.g., wheat, rye, and corn) and other starch crops (e.g., potato) [5••,6,14,15]. Calculations of the energy potentials of dedicated bio-energy crops generally multiply the area assumed to be available for bio-energy crops by the expected yield per unit area and year:

$$\text{Bio-energy potential } [\mathrm{J/yr}] = \text{area } [\mathrm{m}^2] \times \text{yield } [\mathrm{J/m^2/yr}]$$

Discrepancies between bio-energy potentials reported in the literature result from differences in both, area and yield assumptions [11,16]. The main issue is therefore to understand the factors that constrain area and yields, for example, area needed for food, water availability, technology, and nature conservation. We therefore focused on recent studies that explicitly report area and yield data underlying their bio-energy crop potential estimates.

Area available for bio-energy crops

Large discrepancies exist in the literature on the area available globally for cultivation of bio-energy crops: projected areas for bio-energy crops range from 0.6 to 37 million km^2, that is, 0.4–28% of the earth's lands except Greenland and Antarctica (Table 1). The largest area of bio-energy plantations in 2050 in the recent literature is 2.4 times larger than the area currently used for cropland or almost equal to the current area of human-used forests (see Table 1a) [17]. The discrepancies between studies result from different assumptions on constraints such as area requirements for food and fibre production, urban and infrastructure areas, areas with poor soils, low temperatures, limited water availability, protection of high-biodiversity areas and from the difficulties involved in judging the availability and suitability of land for energy crops on the basis of available land-use and land-cover data.

Most studies calculate available areas using a 'land balance' approach, that is, cultivable areas are identified

Table 1

Global area and its net primary productivity (NPP) in 2000 and results from studies of future area availability for bio-energy crops and energy potentials from dedicated bio-energy plantations

Land-use category	Area [mio. km^2]	Aboveground productivity [MJ/m^2/yr]	Global above-ground NPP [EJ/yr]
(a) Global area and productivity of terrestrial systems in the year 2000 [1••,17]			
Urban areas	1.4	4.6	6
Cropland	15.2	12.8	195
Grazing land	46.9	8.1	379
Human-used forests (forestry)	35.0	14.9	520
Unused productive land	15.8	8.7	137
Unproductive land	16.2	0.1	2
Global total land mass except Greenland, Antarctica	130.4	9.5	1239

Study	Area [mio. km^2]	Yield [MJ/m^2/yr]	Global bio-energy potential [EJ/yr]
(b) Global total estimates of bio-energy potentials from dedicated bio-energy plantations, various recent studies			
(1) Studies referring to the current situation or points in time before 2050			
Field *et al*. [8], current abandoned farmland	3.9	6.9	27
Campbell *et al*. [7], current abandoned farmland	3.9–4.7	8.2–8.7	32–41
Sims *et al*. [15], potential for 2025	0.6–1.4	7.9–24	5–34
(2) Original studies referring to 2050			
Erb *et al*. [22••], biomass-balance food/feed/bio-energy	2.3–9.9	12–13	28–128
WBGU [5••], vegetation modelling with LPJmL	2.5–5.2	14–23	34–120
van Vuuren *et al*. [23••], abandoned farmland, grassland	<6	19–60	65–300
Hoogwijk *et al*. [59], abandoned farmland, 'rest' land	29–37	10–18	300–650
Smeets *et al*. [11], surplus pasture and farmland	7.3–35.9	29–39	215–1272
(3) Reviews referring to 2050			
MNP [9]/Dornburg *et al*. [10•], surplus land, improved technology	n.a.	n.a.	120–330
IEA [6], 'sustainable' energy-crops	n.a.	n.a.	190–330
IEA [6], surplus and marginal land	n.a.	n.a.	60–810

Data given in different units in the original studies were converted to Joules assuming 1 kg dry matter biomass = 0.5 kg carbon = 18.5 MJ/kg. If yields were not reported, we calculated average yields by dividing total bio-energy potentials by areas as reported in the respective study. Note that these are primary energy potentials that do not consider losses in conversion (e.g., liquefaction, gasification).

depending on soil, climate and terrain characteristics, often based on the global agro-ecological zones methodology [18] or similar approaches [19], from which the area already cultivated or required in the future is subtracted. This approach has, however, been criticized because (1) cultivable land may be overestimated if uncultivable enclosures such as hills, rock, outcrops, and minor water bodies are neglected or underestimated, (2) already cultivated land is often underestimated and (3) land demand for purposes other than cropping, in particular grazing and settlements, is insufficiently taken into account [20•].

Livestock grazing poses particular methodological difficulties because reliable statistical data are lacking. There is strong evidence that mowing and grazing of livestock are not confined to areas classified as 'pastures' in FAO statistics, and it has recently been argued that most ecosystems dominated by herbaceous plants and shrubs, and even some forests, are grazed, although sometimes with low intensity [17,21]. One problem is that livestock grazing can hardly be detected by remote sensing; another is that a large fraction of grazing animals are kept by subsistence farmers not accurately represented in statistics [2,17,21]. Some studies calculated bio-energy potentials only on 'abandoned farmland' [7,8], an approach that yields low estimates because it neglects the possibility that other land could become available through intensification or land conversion.

In our judgement, methods are therefore needed to estimate area and productivity potentials of land available for bio-energy plantations that consider critical social (e.g., food production) and environmental (e.g., biodiversity conservation) goals. Three studies have recently reported spatially explicit data on areas available for bio-energy crops in 2050 that considered sustainability-related constraints. Erb *et al.* [22••] calculated the balance between the NPP of areas potentially available for roughage supply [1••] and roughage demand of livestock [2]. This allowed deriving estimates of area availability for bio-energy crops for different scenarios regarding diets, cropland yields and feeding efficiency of livestock based on the assumption that grazing intensity could be increased in those regions where it was lower than elsewhere. The WBGU [5••] derived estimates of the future availability of area for bio-energy crops by excluding biodiversity hotspots, nature conservation areas, wetlands and areas with long carbon payback times. Their study assumed two variants on cropland expansion (constant, plus 1.2 million km^2). van Vuuren *et al.* [23••] calculated bio-energy crop potentials on abandoned farmland and natural grasslands, assuming accessibility factors of 75% for abandoned farmland and 50% for natural grasslands. Food demand, water scarcity, biodiversity protection and land degradation were also considered. Information on the methods applied in these studies, including an analysis of their strengths and limitations, is given in the SOM.

Yields

The survey summarized in Table 1b shows that yield expectations of bio-energy plantations also differ widely, from 6.9 to 60 MJ/m^2/yr (approximately 0.4–3.3 kg/m^2/yr), that is, by a factor of almost 9. Differences in yields of bio-energy plantations largely result from assumptions on land suitability, choice of bio-energy crop (yields of lignocellulosic crops and perennial grasses are higher than those of food crops) and management (e.g., fertilizer input) [5••,23••,10•]. Some studies summarized in Table 1 assumed yields that exceed the globally average NPP of the most productive land-use category (forestry) by a factor of 4. A recent study used large agricultural databases to analyze yield assumptions in various bio-energy studies and concluded that yields had often been overestimated by more than 100% [24••]. Moreover, limitations in the availability of critical resources such as water [25] are likely to constrain yield increases in many regions. Further research on how to extrapolate yields from field trials to larger areas is therefore needed.

While high biomass yields have been reported in field trials under controlled conditions, it seems questionable whether these yields can be extrapolated to large areas. Some authors have argued that the NPP of potential vegetation, that is, the vegetation that would be expected in the absence of land use, were a good approximation of the upper limit of yields over large areas and accordingly used NPP as proxy for yields of bio-energy plantations [7,8,22••]. This approach might underestimate achievable yields under intensive management, despite the fact that the globally average NPP of croplands is currently 35% lower than their potential NPP [1••]. One reason for this is that the growth period of many crops is lower than that of natural vegetation. The WBGU has recently used LPJmL, a dynamic global vegetation model, to simulate yields of bio-energy crops with and without irrigation and found yield potentials of up to 23 MJ/m^2/yr [5••], a bit more than twice current average global aboveground NPP.

Global potential of bio-energy crops in 2050

Table 1a suggests that only one quarter of the earth's land is devoid of human use, and as little as 11% of current aboveground NPP takes place there. Urban and infrastructure areas occupy about 1% of the earth's surface and can be expected to grow considerably until 2050. The aboveground NPP of urban areas, cropland and grazing land amounts to 580 EJ/yr, of which humans currently harvest 217 EJ/yr for food, feed, fibre and bio-energy (including 28 EJ/yr of unused cropland residues [1••,2]). A notable proportion — perhaps up to 70 EJ/yr — of the difference (363 EJ/yr) is biomass burned in human-induced fires [3].

According to FAO projections, cropland areas are expected to grow until 2050 by 9% and average yields on cropland by 54% compared to the year 2000, thus indicating that most of the expected increase in food production can be met through yield increases [26]. Based on extrapolations of regionally specific biomass input-output ratios of livestock and four different assumptions on diet changes, the study by Erb *et al.* [22••] concluded that 2.3–9.9 million km^2 could be available in 2050 for bio-energy crop plantations if the most suitable grazing areas were intensified as far as possible. The WBGU [5••] combined various assumptions on constraints for available areas (no deforestation, growth in cropland areas, exclusion of high-biodiversity areas, *etc.*) with assumptions on irrigation and used a dynamic global vegetation model to estimate bio-energy yields. Despite their completely different methodologies, both studies found an almost identical range of global bio-energy crop potentials of ≈30–120 EJ/yr. A third recent study by van Vuuren *et al.* [23••] used the IMAGE model to calculate global bio-energy crop potentials, thereby considering constraints such as soil degradation and water scarcity. The constrained scenarios in this study span a similar but somewhat higher range (65–148 EJ/yr).

Table 2 reports estimates global bio-energy crop potentials derived as arithmetic mean of minimum, maximum and intermediate estimates of these three studies. We are aware that each of these studies has its limitations (see SOM). Nevertheless, we believe that these ranges give a useful indication of possible orders of magnitude because they are based on completely different, complementary methods and yet still arrived at largely similar results that are plausible when compared to the above-quoted estimates of the productivity of the areas on which such bio-energy plantations could be potentially located.

Crop residues, animal manures and municipal solid wastes

Organic residues and wastes, including crop residues, animal manures and municipal solid wastes (MSWs), represent a sizeable global bio-energy resource. Rational utilization of wastes and residues can often produce energy cost-effectively and minimize environmental impacts from alternative management or disposal methods.

Two types of residues are associated with crop production: field (primary) and processing (secondary) residues

Table 2

Arithmetic mean of minimum, maximum and intermediate estimates of the global potential to grow dedicated bio-energy crops according to three recent studies [5,22**,23**]**

	Mean of minimum estimates [EJ/yr]	Mean of maximum estimates [EJ/yr]	Mean of intermediate estimates [EJ/yr]
North America	6	21	13
Western Europe	2	8	5
Pacific OECD	3	8	5
Central and Eastern Europe	1	3	2
Former Soviet Union	3	9	6
Centrally planned Asia, China	5	15	8
South Asia	1	3	2
Other Pacific Asia	2	7	4
Middle East and North Africa	1	3	1
Latin America and the Caribbean	11	34	21
Sub-Saharan Africa	10	23	16
Global total	44	133	81

(Figure 1). Recoverable energy potentials of both types of residues can be estimated from annual crop production using a number of factors such as the recoverable fraction of residue production, residue to product (or crop) ratio and gross heating value.

Assuming recoverable fraction values for different crops of 0.5–0.75, Hakala *et al.* [27] estimated the global technical potential of field residues in 2050 at 38–41 EJ/yr. Adding the process residue potential of 16 EJ/yr [11], the total technical potential of crops residues would be 54–57 EJ/yr. Other authors suggested global technical bio-energy potentials from crop residues of 10–32 EJ/yr [28] and 46–66 EJ [11]. Based on region-specific and crop-specific factors and FAO crop production forecasts [26], one of the authors (SCB) has recently estimated the annual technical global crop residue energy potential in 2050 to be 49 EJ/yr (Table 3). Differences between the results of these studies are mainly due to different assumptions on future crop production and on the recoverable fraction and other factors.

Additional bio-energy can be derived from animal manures (secondary residues) and municipal solid wastes (MSW, i.e. tertiary residues). The global potential of recoverable MSW in 2050 has been reported to be 17 EJ/yr [11] and 1–3 EJ/yr [28]. These values can be compared with the value of 11 EJ/yr recently estimated by one of the authors (SCB, Table 3). The energy equivalent of recoverable manures (the biogas potential is approximately three quarters lower) in 2050 has been reported to be 9–25 EJ/yr [28] and 25 EJ/yr [29]. One of the authors (SCB) recently estimated the potential to be 39 EJ/yr (Table 3). Differences in the above-quoted energy potentials are mainly due to differences in projected waste or residue generation values and recoverable fractions. The global total energy potential of crop residues, MSW and animal manures is approximately 100 EJ/yr (Table 3) which is in line with other studies [10•].

Table 3

Technical primary energy potential of crop residues, MSW and animal manures in 2050 (Bhattacharya, unpublished)

	Crop residues [EJ/yr]	MSW [EJ/yr]	Animal manures* [EJ/yr]	Total [EJ/yr]
North America	4	1	4	9
Western Europe	3	1	3	7
Pacific OECD	1	0	2	3
Central and Eastern Europe	1	0	1	1
Former Soviet Union	2	0	2	4
Centrally planned Asia, China	9	2	5	16
South Asia	9	1	8	17
Other Pacific Asia	5	1	1	7
Middle East and North Africa	2	1	2	5
Latin America and the Caribbean	11	2	8	21
Sub-Saharan Africa	5	1	4	10
Global total	49	11	39	100

* Energy equivalent of recoverable manures. The energy equivalent of the amount of biogas that could be produced from these manures is approximately one quarter of the figures given here.

Table 4

Estimate of the technical bio-energy potential from forestry residues in 2050. Sources: calculated based on Ref. [32]

	Low estimate [EJ/yr]	High estimate [EJ/yr]	Arithmetic mean [EJ/yr]
North America	6	12	9
Western Europe	4	7	6
Pacific OECD	1	2	2
Central and Eastern Europe	1	2	2
Former Soviet Union	2	4	3
Centrally planned Asia, China	2	3	3
South Asia	0	0	0
Other Pacific Asia	0	1	1
Middle East and North Africa	0	0	0
Latin America and the Caribbean	2	4	3
Sub-Saharan Africa	0	1	1
Global total	19	35	27

Forestry residues

The technical potential of forest residues for energy production is defined as the total amount of surplus forest residues that can be collected without affecting commercial wood production. Three categories of forestry residues can be discerned (Figure 1): primary (from fellings, e.g., fuel wood, or as residues from thinning), secondary (processing wastes, e.g., sawdust) and tertiary (available after final use, e.g., waste wood). The global potential of forestry residues has been assessed by various studies [4,30,31,32]. Anttila *et al.* [32] present a recent estimate of the current primary forestry residue potential. Their estimate of a global bio-energy potential of 5–9 EJ/yr includes logging residues from current fellings as well as stem wood and logging residues from additional fellings. These are the only data that are available for the 11 regions used in this paper. The global results are low compared to estimates for the year 2050 [4,30,31] that found bio-energy potentials of 12–74 EJ/yr from forestry. The difference largely results from the fact that Anttila *et al.* did not include secondary and tertiary residues and focused on the present situation. Apart from that, the results of Anttila *et al.* are similar to those of Smeets *et al.* [31], except for Asia. This is partly due to the differences in regions consuming large amounts of forestry products because the potentials for secondary residues are higher there. According to [31], secondary and tertiary residues from the wood processing industry and waste management could deliver 3–5 times more energy than primary residues. We therefore used a factor of 4 to extrapolate total forestry residue potentials for the 11 regions used here from [32] to derive the values reported in Table 4.

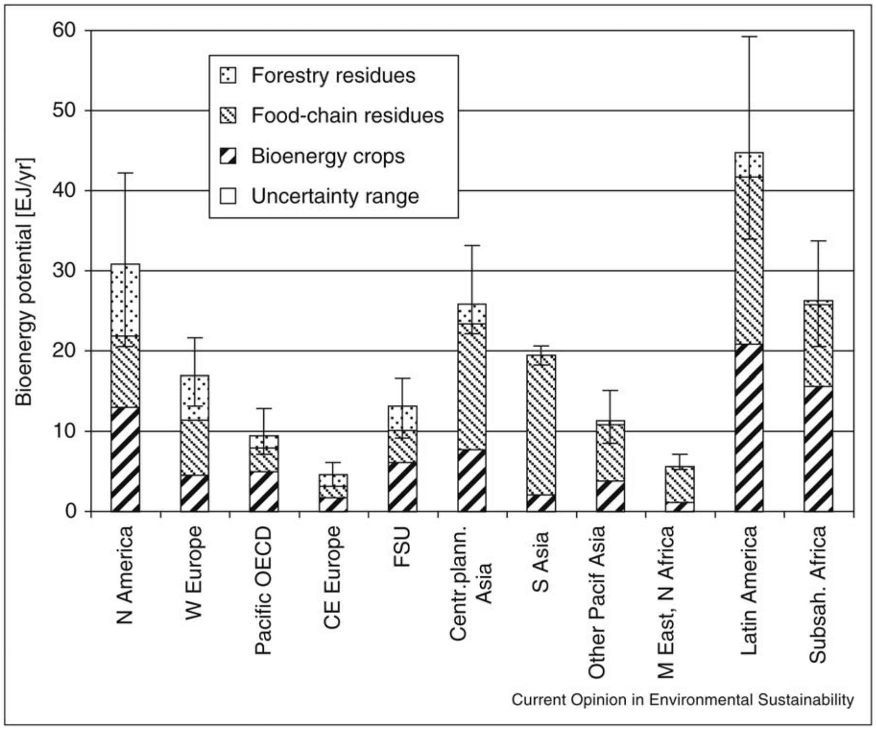
Discussion and conclusions

Figure 2 summarizes the three components of the technical bio-energy potential in 2050 based on the values reported in Tables 2–4. We find a technical global bio-energy potential in 2050 of approximately 210 (160–270) EJ/yr. Dedicated bio-energy crops contribute 81 (44–133) EJ/yr which is at the lower end of the potentials found in previous assessments (Table 1), but higher than the potentials identified on 'abandoned farmland' alone [7,8]. The result seems reasonable when compared with global terrestrial aboveground NPP (Table 1). A large fraction of the bio-energy potential is found to be related to the use of currently unused residues, that is, efficiency gains in socioeconomic biomass utilization and flow chains. This finding underlines earlier work on the importance of a 'cascade utilization' of biomass, that is, the integrated optimization of food, fibre and energy supply from biomass [5••,33,34]. Comparisons of livestock energy balances across time and between regions suggest that there might be a potential to increase feeding efficiencies that could allow for increased bio-energy production [22••,35]. However, using this potential might have significant social impacts, in particular on subsistence farming systems, if policies are not appropriately designed [34].

Our findings underline the importance of future diets for global bio-energy potentials [22••,10•,34,35]. Two mechanisms are relevant here: (1) land requirements for food and feed production constrain the area available for dedicated bio-energy crops, in particular when livestock is taken into account [22••,35,36]. (2) The 'food-chain residue' potential (crop residues, manures, and MSW) also depends on agricultural production chains and food demand.

Adequately feeding a world with approximately 9 billion people in 2050 will require substantial yield increases, larger agricultural areas, or both. Diets are bound to change as a result of growing incomes and GDP growth additionally drives up the demand for other biomass-based resources. A combination of adequate food supply with substantial levels of energy crop production will require a growth in the yields of food and feed crops along past trajectories. Recent studies demonstrate that there are strong links between bio-energy potentials and agricultural technology, in particular yields of food and energy crops and feeding efficiencies [22••,10•,36,37]. Whether yield increases as forecast by the FAO [26]

Figure 2



Technical bio-energy potentials in 2050, breakdown to 11 regions. 'Food-chain residues' are crop residues, animal manures and MSW. Whiskers identify uncertainties as reported in Tables 2–4.
Source: Tables 2–4.

can be sustained, for example, based on high-yielding varieties, large-scale optimum management and precision farming, has been questioned. Much of the best-suited cropland is already used and rates of yield increases are falling in some regions as they approach limits set by soil and climate [38]. Soil degradation and depletion of nutrient stocks in soils are additional challenges [39]. Substantial investments will be indispensable for maintaining growth in crop yields [40], and economic constraints might prevent the realization of yield potentials [41]. However, if yields of food and energy crops should grow significantly faster than assumed here, the energy crop potential would also be substantially larger [11,10,SOM].

Few assessments of global bio-energy potentials have considered the possible effect of future climate change, consequently this connection is poorly understood [6]. Climate change may influence global bio-energy potentials in two ways: (1) directly through its effects on yields of bio-energy crops, and (2) indirectly through its impacts on the food system. Plants following the C3 photosynthetic pathway such as poplars and willows respond to rising CO_2 concentrations with increased productivity if water and nutrients are not limiting [42]. The magnitude and long-term development of this 'CO_2 fertilization effect' are still debated, but results from free-air CO_2 enrichment (FACE) experiments show sustained yield increases of up to 20% in poplar short-rotation coppice plantations [43]. On the other hand, there is evidence that crops grown under elevated CO_2 concentrations might be more susceptible to insect pests [44]. Considering direct and indirect effects, a recent study [36] found that global bio-energy potentials may vary by a factor of two, depending on the strength of the CO_2 fertilization effect.

Many plants also use water more efficiently under elevated CO_2 concentrations due to reduced stomatal conductance and leaf transpiration [45]. Observations of poplar short-rotation coppice revealed, however, that whole-tree water use increased with CO_2 as a result of higher leaf area [46]. Perennial C4 grasses show little response to higher ambient CO_2, but generally require large amounts of water during the growing season [47]. The responses of dense monocultures of perennial crops to changes in climate are complex and difficult to predict because experience in large-scale plantations under realistic field conditions is missing. However, a massive expansion of energy crops is likely to have significant effects on regional water resources and fertilizer use.

The impacts of changes in temperature and rainfall on crop yields are going to differ significantly among regions.

It is mostly assumed that negative effects on agriculture will outweigh any benefits, above all in developing countries, mostly due to increased water stress [48–50]. The area required to cultivate food crops might therefore expand significantly in the coming decades to meet the demand from a rising and more affluent world population [51], which would reduce land availability for energy crops. A recent study suggested that changes in the area needed for food production resulting from climate change might have a much larger effect on future bio-energy potentials than the direct effect of climate change on the yields of energy crops [36]. Increasing competition for water resources, in particular due to rising food demand and water pollution, might also limit the expansion of bio-energy plantations [52]. Food crops, and thus first-generation energy crops, seem to be more vulnerable to higher climate variability and more frequent extreme events than perennial lignocellulosic species. Plant breeding might further reduce the vulnerability of modern energy crops to climate change, but breeding efforts have just begun and their prospects are uncertain [53]. Avoiding large-scale monocultures could help to increase the resilience of bio-energy plantations to more frequent weather extremes [54].

Environmental impacts of bio-energy policies [55] and socioeconomic aspects of bio-energy production, for example, costs or interactions with food prices, are beyond the scope of this review. Both issues will be decisive for future levels bio-energy production and use, in particular as it seems likely that environmental impacts per unit of bio-energy depend on the total volume of bio-energy produced [56]. Recent studies suggest that lignocellulosic crops and residues are preferable to first-generation biofuel crops in terms of both costs and environmental impacts [14]. However, there are concerns that removing residues from the field could have a negative impact on soil carbon and fertility which might reduce the sustainable potential of crop residues [5••,57,58•].

In conclusion, our review has led us to believe that no scientific study is at present available that would satisfactorily resolve the many scientific issues related to future mid-term bio-energy potentials. The most pressing uncertainties relate to the availability and suitability of land for energy crops, the development and potential of yield increases, future area demand for food, conservation and other purposes, trade-offs with other environmental goals (e.g., biodiversity), water availability and climate impacts. Uncertainties remain, even beyond the obvious fact that human behavioural patterns as intimately related to cultural and other socioeconomic factors as diets are almost impossible to predict. While each of the studies upon which our results were mainly based did, in our judgment, succeed in advancing our understanding of the intricate feedbacks between changes in land use, food, feed, fibre and bio-energy production with respect to some critical factors, none was devoid of shortcomings (see SOM). While we believe that the synthesis of these studies does contribute significant insights on our current knowledge on future bio-energy potentials under various sustainability-related constraints, we clearly see that further work is required to better understand the inter-linkages between food, fibre and bio-energy systems in order to identify socially, economically and environmentally sustainable options for future land-use and bio-energy strategies.

Conflict of interest

None.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.cosust.2010.10.007.

References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. Haberl H, Erb K-H, Krausmann F, Gaube V, Bondeau A, Plutzar C,
•• Gingrich S, Lucht W, Fischer-Kowalski M: **Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems**. *Proc Natl Acad Sci USA* 2007, **104**:12942-12947.

Consistently merging statistical data on agriculture and forestry with land-use data from remote sensing and results from a dynamic global vegetation model (DGVM), this study quantified and mapped global NPP, its anthropogenic alteration as well as human biomass harvest.

2. Krausmann F, Erb K-H, Gingrich S, Lauk C, Haberl H: **Global patterns of socioeconomic biomass flows in the year 2000: a comprehensive assessment of supply, consumption and constraints**. *Ecol Econ* 2008, **65**:471-487.

3. Lauk C, Erb K-H: **Biomass consumed in anthropogenic vegetation fires: global patterns and processes**. *Ecol Econ* 2009, **69**:301-318.

4. Sims REH, Schock RN, Adegbululgbe A, Fenhann J, Konstantinaviciute I, Moomaw W, Nimir HB, Schlamadinger B, Torres-Martinez J, Turner C *et al.*: **Energy supply**. In *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Edited by Metz B, Davidson A, Bosch PR, Dave R, Meyer LA. Cambridge University Press; 2007. . pp. 250–322..

5. WBGU: *Future Bioenergy and Sustainable Land Use*. Earthscan;
•• 2009.

This study contains a broad overview of economic, social and environmental aspects of future bioenergy use and its potential effects on land systems. It uses up-to-date LCA methods to quantify GHG and other emissions from bio-energy production chains and dynamic global vegetation modelling to assess bio-energy crop potentials.

6. Bauen A, Berndes G, Junginger M, Londo M, Vuille F, Ball R, Bole T, Chudziak C, Faaij A, Mozaffarian H: *Bioenergy — A Sustainable and Reliable Energy Source. A Review of Status and Prospects*. International Energy Agency; 2009.

7. Campbell JE, Lobell DB, Genova RC, Field CB: **The global potential of bioenergy on abandoned agriculture lands**. *Environ Sci Tech* 2008, **42**:5791-5795.

8. Field CB, Campbell JE, Lobell DB: **Biomass energy: the scale of the potential resource**. *Trends Ecol Evol* 2008, **23**:65-72.

9. Dornburg V, Faaij APC, Verweij P, Langeveld H, van de Ven G, van Keulen H, van Diepen K, Meeusen M, Banse M, Ros J *et al.*: *Biomass Assessment. Assessment of Global Biomass Potentials and Their Links to Food, Water, Biodiversity, Energy Demand and Economy*. Netherlands Environmental Assessment Agency; 2008.

10. • Dornburg V, van Vuuren D, van de Ven G, Langeveld H, Meeusen M, Banse M, van Oorschot M, Ros J, Jan van den Born G, Aiking H *et al.*: **Bioenergy revisited: key factors in global potentials of bioenergy**. *Energ Environ Sci* 2010, **3**:258-267.

This study provides a useful review of factors that influence future bioenergy potentials. It includes a sensitivity analysis of some of those factors based on own calculations that shows the importance of taking biodiversity conservation, water limitations, food demand and other factors that could constrain future bio-energy potentials into account.

11. Smeets EMW, Faaij APC, Lewandowski IM, Turkenburg WC: **A bottom-up assessment and review of global bio-energy potentials to 2050**. *Progr Energ Combust Sci* 2007, **33**:56-106.

12. Smith VH, Sturm BSM, deNoyelles FJ, Billings SA: **The ecology of algal biodiesel production**. *Trends Ecol Evol* 2010, **25**:301-309.

13. Florentinus A, Hamelinck C, Lint Sd, Iersel Sv: *Worldwide Potential of Aquatic Biomass*. Ecofys; 2008.

14. de Wit M, Faaij A: **European biomass resource potential and costs**. *Biomass Bioenerg* 2010, **34**:188-202.

15. Sims REH, Hastings A, Schlamadinger B, Taylor G, Smith P: **Energy crops: current status and future prospects**. *Glob Change Biol* 2006, **12**:2054-2076.

16. Marland G, Obersteiner M: **Large-scale biomass for energy, with considerations and cautions: an editorial comment**. *Clim Change* 2008, **87**:335-342.

17. Erb K-H, Gaube V, Krausmann F, Plutzar C, Bondeau A, Haberl H: **A comprehensive global 5 min resolution land-use dataset for the year 2000 consistent with national census data**. *J Land Use Sci* 2007, **2**:191-224.

18. IIASA, FAO: *Global Agro-Ecological Zones 2000*. International Institute for Applied Systems Analysis, Food and Agriculture Organization; 2000.

19. Ramankutty N, Foley JA, Norman J, McSweeney K: **The global distribution of cultivable lands: current patterns and sensitivity to possible climate change**. *Global Ecol. Biogeogr.* 2002, **11**:377-392.

20. • Young A: **Is there really spare land? A critique of estimates of available cultivable land in developing countries**. *Environ Dev Sustain* 1999, **1**:3-18.

In this paper, the experienced practitioner and land developer A. Young succinctly summarizes his critique of the 'land-balance approach' for determining cultivable land. The strength of this study lies in Young's enormous practical experience.

21. FAO: *Livestock's Long Shadow — Environmental Issues and Options*. Food and Agriculture Organisation; 2006.

22. •• Erb KH, Haberl H, Krausmann F, Lauk C, Plutzar C, Steinberger JK, Müller C, Bondeau C, Waha K, Pollack G: *Eating the Planet: Feeding and Fuelling the World Sustainably, Fairly and Humanely — A Scoping Study*Institute of Social Ecology, Potsdam Institute of Climate Impact Research; 2009.

This study develops a biomass-balance model that consistently integrates NPP, land use, agricultural technology (yields, livestock feed balances) and final use of food, fibre and bio-energy. The model is used to determine the biophysical feasibility of 72 sets of assumptions ('scenarios') on future diets, cropland expansion, livestock feeding efficiencies and cropland yields. Its strength is a large database for the year 2000 that is consistent across regions, domains and sectors.

23. •• van Vuuren DP, Van Vliet J, Stehfest E: **Future bio-energy potential under various natural constraints**. *Energ Pol* 2009, **37**:4220-4230.

This recent modelling study used IMAGE to look into possible constraints on bio-energy resulting from other land uses as well as limits such as soil degradation or water availability. It shows that such constraints are quite important in determining global bio-energy potentials and also discusses economic issues such as cost curves of bio-energy provision.

24. •• Johnston M, Foley JA, Holloway T, Kucharik C, Monfreda C: **Resetting global expectations from agricultural biofuels**. *Environ Res Lett* 2009:4. doi:10.1088/1748-9326/4/1/014004..

Using large agricultural databases, this study makes a strong case that previous assessments were overly optimistic when extrapolating plot-sized field trials of bio-energy production to large areas. Its main conclusion is that bio-energy crop yields are bound to be a lot lower under 'real world' conditions than in field trials and that more research on realistic yield expectations is required.

25. Gerten D, Rost S, Bloh W, Lucht W: **Causes of change in 20th century global river discharge**. *Geophys Res Lett* 2008:35. doi:10.1029/2008GL035258..

26. FAO: *World Agriculture: Towards 2030/2050 — Interim Report. Prospects for Food, Nutrition, Agriculture and Major Commodity Groups*Food and Agricultural Organization; 2006.

27. Hakala K, Kontturi M, Pahkala K: **Field biomass as global energy source**. *Agric Food Sci* 2009, **18**:347-365.

28. Hoogwijk MM: *On the Global and Regional Potential of Renewable Energy Sources*. Universiteit Utrecht; 2004.

29. Johansson TB, Kelly H, Reddy AKN, Williams RH (Eds): *Renewable Energy, Sources for Fuels and Electricity*. Earthscan, Island Press; 1993.

30. Berndes G, Hoogwijk M, van den Broek R: **The contribution of biomass in the future global energy supply: a review of 17 studies**. *Biomass Bioenerg* 2003, **25**:1-28.

31. Smeets EMW, Faaij APC: **Bioenergy potentials from forestry in 2050**. *Clim Change* 2007, **81**:353-390.

32. Anttila P, Karjalainen T, Asikainen A: *Global Potential of Modern Fuelwood*. Finnish Forest Research Institute; 2009.

33. Haberl H, Geissler S: **Cascade utilisation of biomass: how to cope with ecological limits to biomass use**. *Ecol Eng* 2000, **16**:S111-S121.

34. Tilman D, Socolow R, Foley JA, Hill J, Larson E, Lynd L, Pacala S, Reilly J, Searchinger T, Somerville C *et al.*: **Beneficial biofuels — the food, energy, and environment trilemma**. *Science* 2009, **325**:270-271.

35. Stehfest E, Bouwman L, Vuuren DPv, Elzen MGJd, Eickhout B, Kabat P: **Climate benefits of changing diet**. *Clim Change* 2009, **95**:83-102.

36. Haberl H, Erb K-H, Krausmann F, Bondeau A, Lauk C, Müller C, Plutzar C, Steinberger J: **Global bioenergy potentials from agricultural land in 2050: Sensitivity to climate change, diets and yields**. *Biomass Bioenerg*, forthcoming.

37. Lotze-Campen H, Popp A, Beringer T, Müller C, Bondeau A, Rost S, Lucht W: **Scenarios of global bioenergy production: the trade-offs between agricultural expansion, intensification and trade**. *Ecol Modell* 2010, **221**:2188-2196.

38. Tilman D, Cassman KG, Matson PA, Naylor R, Polasky S: **Agricultural sustainability and intensive production practices**. *Nature* 2002, **418**:671-677.

39. Cassman KG: **Ecological intensification of cereal production systems: yield potential, soil quality, and precision agriculture**. *Proc Natl Acad Sci USA* 1999, **96**:5952-5959.

40. Kahn BM, Zaks D, Fulton M, Dominik M, Soong E, Baker J, Cotter L, Reilly J, Foley JA, Schneider G *et al.*: *Investing in Agriculture: Far-Reaching Challenge, Significant Opportunity, An Asset Management Perspective*DB Climate Change Advisors, Deutsche Bank Group; 2009.

41. Koning N, van Ittersum MK: **Will the world have enough to eat?** *Curr Opinion Environ Sustain* 2009, **1**:77-82.

42. Oliver RJ, Finch JW, Taylor G: **Second generation bioenergy crops and climate change: a review of the effects of elevated atmospheric CO2 and drought on water use and the implications for yield**. *GCB Bioenergy* 2009, **1**:97-114.

43. Liberloo M, Lukac M: **Coppicing shifts CO2 stimulation of poplar productivity to above-ground pools: a synthesis of leaf to stand level results from the POP/EUROFACE experiment**. *New Phytologist* 2009. doi: 10.1111/j.1469-8137.2008.02754.x..

44. Zavala JA, Casteels CL, DeLucia EH, Berenbaum MR: **Anthropogenic increase in carbon dioxide compromises plant defense against invasive insects**. *Proc Natl Acad Sci USA* 2008, **105**:5129-5133.

45. Ainsworth EA, Long SP: **What have we learned from 15 years of free-air CO2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO2**. *New Phytol* 2005, **165**:351-371.

46. Tricker PJ, Pecciari M, Bunn SM, Vaccari FP, Peressotti A, Miglietta F: **Water use of a bioenergy plantation increases in a future high CO2 world**. *Biomass Bioenerg* 2009, **33**:200-208.

47. Hickman GC, Vanloocke A, Dohleman FG, Bernacchi CJ: **A comparison of canopy evapotranspiration for maize and two perennial grasses identified as potential bioenergy crops**. *GCB Bioenergy* 2010, **2**:157-168.

48. Lobell DB, Burke MB, Tebaldi C, Mastrandrea MD, Falcon WP, Naylor RL: **Prioritizing climate change adaptation needs for food security in 2030**. *Science* 2008, **319**:607-610.

49. Easterling W, Aggarwal P, Batima P, Brander K, Erda L, Howden M, Kirilenko A, Morton J, Soussana J-F, Schmidhuber J *et al.*: **Food, fibre and forest products**. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Edited by Parry ML, Canziani OF, Palutikof P, van der Linden J, Hanson CE. Cambridge University Press; 2007. . pp. 273–313.

50. Schlenker W, Lobell DB: **Robust negative impacts of climate change on African agriculture**. *Environ Res Lett* 2010:5. doi:10.1088/1748-9326/5/1/014010..

51. Rockström J, Falkenmark M, Karlberg L, Hoff H, Rost S, Gerten D: **Future water availability for global food production: the potential of green water for increasing resilience to global change**. *Water Resour Res* 2009, **45**:1-16.

52. Gerbens-Leenes W, Hoekstra AY, van der Meer TH: **The water footprint of bioenergy**. *Proc Natl Acad Sci USA* 2009, **106**:10219-10223.

53. Karp A, Shield I: **Bioenergy from plants and the sustainable yield challenge**. *New Phytol* 2008, **179**:15-32.

54. Tilman D, Hill J, Lehmann C: **Carbon-negative biofuels from low-input high-diversity grassland biomass**. *Science* 2006, **314**:1598-1600.

55. Searchinger T, Heimlich R, Houghton RA, Dong F, Elobeid A, Fabiosa J, Tokgoz S, Hayes D, Yu TH: **Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change**. *Science* 2008, **319**:1238-1240.

56. Searchinger TD: **Biofuels and the need for additional carbon**. *Environ Res Lett* 2010:5. doi:10.1088/1748-9326/5/2/024007..

57. Lal R: **World crop residues production and implications of its use as a biofuel**. *Environ Int* 2005, **31**:575-584.

58. • Blanco-Canqui H, Lal R: **Crop residue removal impacts on soil productivity and environmental quality**. *Crit Rev Plant Sci* 2009, **28**:139-163.

This review summarizes the current knowledge on the impacts of crop residue removal on soil properties, crop yields, and soil erosion across a wide range of soils and ecosystems. The review suggests that residue removal adversely impacts near-surface soil physical, chemical, and biological properties. It calls for more research to develop sustainable practices that maintain yields and soil quality.

59. Hoogwijk M, Faaij A, Eickhout B, de Vries B, Turkenburg W: **Potential of biomass energy out to 2100, for four IPCC SRES land-use scenarios**. *Biomass Bioenergy* 2005, **29**:225-257.