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REVIEW

Bioenergy and climate change mitigation: an assessment

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Abstract

Bioenergy deployment offers significant potential for climate change mitigation, but also carries considerable risks. In this review, we bring together perspectives of various communities involved in the research and regulation of bioenergy deployment in the context of climate change mitigation: Land-use and energy experts, land-use and integrated assessment modelers, human geographers, ecosystem researchers, climate scientists and two different strands of life-cycle assessment experts. We summarize technological options, outline the state-of-the-art knowledge on various climate effects, provide an update on estimates of technical resource potential and comprehensively identify sustainability effects. Cellulosic feedstocks, increased end-use efficiency, improved land carbon-stock management and residue use, and, when fully developed, BECCS appear as the most promising options, depending on development costs, implementation, learning, and risk management. Combined heat and power, efficient biomass cookstoves and small-scale power generation for rural areas can help to promote energy access and sustainable development, along with reduced emissions. We estimate the sustainable technical potential as up to 100 EJ: high agreement; 100–300 EJ: medium agreement; above 300 EJ: low agreement. Stabilization scenarios indicate that bioenergy may supply from 10 to 245 EJ yr^{-1} to global primary energy supply by 2050. Models indicate that, if technological and governance preconditions are met, large-scale deployment (>200 EJ), together with BECCS, could help to keep global warming below 2° degrees of preindustrial levels; but such high deployment of land-intensive bioenergy feedstocks could also lead to detrimental climate effects, negatively impact ecosystems, biodiversity and livelihoods. The integration of bioenergy systems into agriculture and forest landscapes can improve land and water use efficiency and help address concerns about environmental impacts. We conclude that the high variability in pathways, uncertainties in technological development and ambiguity in political decision render forecasts on deployment levels and climate effects very difficult. However, uncertainty about projections should not preclude pursuing beneficial bioenergy options.

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Introduction

The recent IPCC report on energy sources and climate change mitigation (SRREN) and the Global Energy Assessment provided comprehensive overviews on bioenergy. An update to these reports is nonetheless important because: (i) many of the more stringent mitigation scenarios (resulting in 450 ppm, but also 550 ppm CO2eq concentration by 2100) heavily rely on a large-scale deployment of bioenergy with CO2 capture and storage (CCS) called BECCS technologies; (ii) there has been a large body of literature published since SRREN, which complement and update the analysis presented in this last report; (iii) bioenergy is important for many sectors and mitigation perspectives as well as from the perspective of developmental goals such as energy security and rural development.

The following text is based mostly, but not exclusively, on a draft of Chapter 11.13 of the Working Group 3 of the 5th Assessment Report of the IPCC (Smith *et al.*, 2014). This article itself represents exclusively the opinions of the authors and not those of the IPCC. It should also be noted that teams of authors worked on subsections and commented on other subsections. The result represents what we consider to be the state-of-the-art on assessing bioenergy, integrating a wide range of literature and perspectives. Given the contentious nature of the literature on bioenergy, it should not be surprising that the authors did not agree on all aspects of this review; thus we attempted to integrate the multiple perspectives present in the literature.

Bioenergy is energy derived from biomass, which can be deployed as solid, liquid and gaseous fuels for a wide range of uses, including transport, heating, electricity production, and cooking. Bioenergy systems can cause both positive and negative effects and their deployment needs to balance a range of environmental, social and economic objectives that are not always fully compatible. The consequences of bioenergy implementation depend on (i) the technology used; (ii) the location, scales and pace of implementation; (iii) the land category used (forest, grassland, marginal lands and crop lands); (iv) the governance systems; and (v) the business models and practices adopted, including how these integrate with or displace the existing land use.

We structure this article in six parts. In section How much bioenergy could be deployed in 2050, we first discuss the technical primary biomass potential for bioenergy. We then elaborate on the specific technological options available to make use of the biomass potential in section Bioenergy technologies. In section GHG emission estimates of bioenergy production systems, we summarize the literature assessing the attributional life-cycle emissions, and the (consequential) life-cycle land-use emissions. In section Future potential deployment in climate mitigation scenarios, we assess the overall role of bioenergy in stabilization scenarios. We then summarize the literature on bioenergy and sustainable development in section Bioenergy and sustainable development and consider trade-offs with other objectives in section Trade-offs and synergies with land, water, food and biodiversity. We conclude with a brief summary.

How much bioenergy could be deployed in 2050

The technical primary biomass potential for bioenergy – from here on referred to as 'technical bioenergy potential' – is the fraction of the theoretical potential (i.e., the theoretical maximum amount of biomass constrained only by biophysical limits) available with current technology. There is no standard methodology to estimate the technical bioenergy potential, which leads to diverging estimates. Most of the recent studies estimating technical bioenergy potentials assume a 'food/fiber first principle' and exclude deforestation, eventually resulting in an estimate of the 'environmentally sustainable bioenergy potential' when a comprehensive range of environmental constraints is considered (Batidzirai *et al.*, 2012).

Recently published estimates that are based in this extended definition of global technical primary biomass potentials in 2050 span a range of almost three orders of magnitude, from <50 EJ yr^{-1} to >1000 EJ yr^{-1} (Hoogwijk *et al.*, 2005, 2009; Smeets *et al.*, 2007; Field *et al.*, 2008; Haberl *et al.*, 2010; Batidzirai *et al.*, 2012). For example, the SRREN reported global technical bioenergy potentials of 50–500 EJ yr^{-1} for the year 2050 (Chum *et al.*, 2011) and the Global Energy Assessment gave a range of 160–270 EJ yr^{-1} (Johansson *et al.*, 2012). The discussion following the publication of these global reports has not resulted in a consensus on the magnitude of the future global technical bioenergy potential, but has helped to better understand some of its many structural determinants (Berndes *et al.*, 2013; Erb *et al.*, 2012; Wirsenius *et al.*, 2010; Dornburg *et al.*, 2010).

Key point 1: How much biomass for energy is technically available in the future depends on the evolution of a multitude of social, political and economic factors, e.g., land tenure and regulation, diets, trade and technology.

Figure 1 shows estimates of the global technical bioenergy potential in 2050 by resource categories. Ranges were obtained from assessing a large number of studies based on a food/fiber first principle and various restrictions regarding resource limitations and environmental concerns but no explicit cost considerations (Chum *et al.*, 2011; Dornburg *et al.*, 2010; GEA, 2012 (Ch. 7,11,20); Gregg & Smith, 2010; Haberl *et al.*, 2010, 2011; Hakala *et al.*, 2009; Hoogwijk *et al.*, 2009, 2005; Rogner *et al.*, 2012; Smeets *et al.*, 2007; Smeets & Faaij, 2007; Van Vuuren *et al.*, 2009). Many studies agree that the technical bioenergy potential in 2050 is at least approximately 100 EJ yr^{-1} with some modeling assumptions leading to estimates exceeding 500 EJ yr^{-1} (Smeets *et al.*, 2007). As stated, different views about sustainability and socioecological constraints lead to very different estimates, with some studies reporting much lower figures.

As shown in Fig. 1, the total technical bioenergy potential is composed of several resource categories that differ in terms of their absolute potential, the span of the ranges –which also reflect the relative agreement/disagreement in the literature- and the implications of utilizing them. Regional differences – which are not addressed here – are also important as the relative size of each biomass resource within the total potential and its absolute magnitude vary widely across countries and world regions.

Forest and agriculture residues

Forest residues include residues from silvicultural thinning and logging; wood processing residues such as sawdust, bark and black liquor; dead wood from natural disturbances, such as storms and insect outbreaks (Smeets & Faaij, 2007; Smeets *et al.*, 2007; Dornburg *et al.*, 2010; Gregg & Smith, 2010; Haberl *et al.*, 2010; Rogner *et al.*, 2012). The use of these resources is in general beneficial. Adverse side effects can be mitigated by
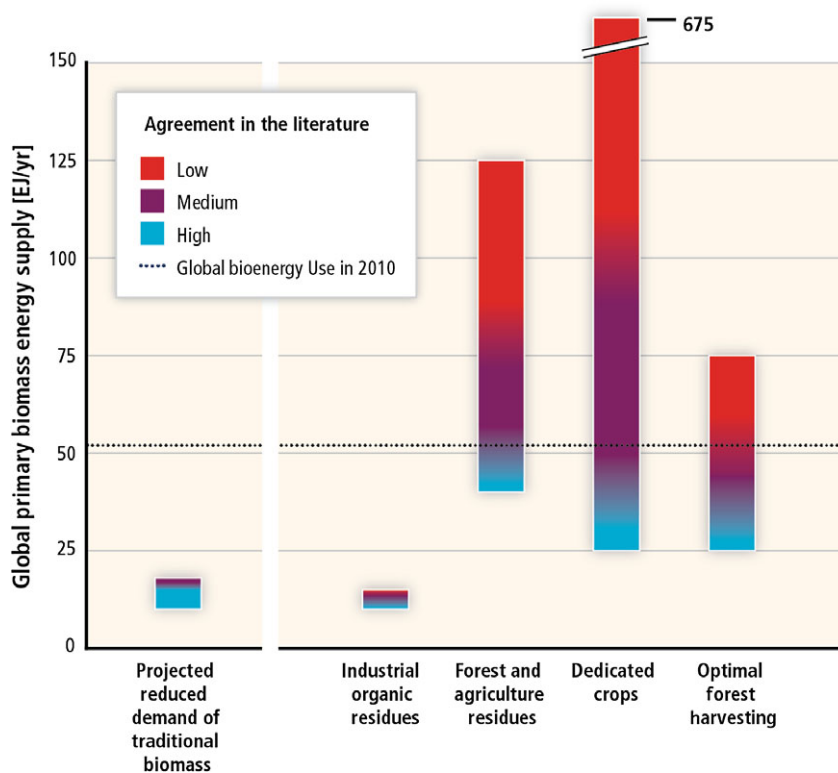
Fig. 1 Global Technical Primary Biomass Potential for Bioenergy by Main Resource Category for the year 2050. The Figure shows the ranges in the estimates by major resource category of the global technical primary biomass potential for bioenergy. The color grading is intended to show qualitatively the degree of agreement in the estimates, from blue (all researchers agree that this level can be attained) to purple (medium agreement) to red (few researchers agree that this level can be attained). In addition, reducing traditional biomass demand by increasing its use efficiency could release the saved biomass for other energy purposes with large benefits from a sustainable development perspective.

controlling residue removal rates considering biodiversity, climate, topography, and soil factors. There is a near term trade-off, particularly in temperate and boreal regions, in that organic matter retains organic C for longer if residues are left to decompose slowly instead of being used for energy (Repo *et al.*, 2012). Agricultural residues include manure, harvest residues (e.g., straw) and processing residues (e.g., rice husks from rice milling) and are also mostly beneficial (Smeets *et al.*, 2007; Hakala *et al.*, 2009; Gregg & Smith, 2010; Haberl *et al.*, 2010, 2011; Chum *et al.*, 2011; Rogner *et al.*, 2012). However, there may be adverse side effects – such as the loss of soil C and associated loss of fertility – associated to harvesting agriculture residues – which may affect the mitigation potential, but are difficult to assess on large scales as they depend on the specific combination of crops, climate and soil conditions (Kochsiek & Knops, 2012). Alternative uses of residues (bedding, use as fertilizer) need to be considered. Both agriculture and forestry residues have varying collection and processing costs, depending on residue quality and dispersal. Densification and storage technologies would enable cost-effective collections over larger areas.

Optimal forest harvesting is defined as the fraction of harvest levels (often set equal to net annual increment) in forests available for additional wood extraction if the projected harvest level resulting from the production of other forest products is taken into account. This includes both biomass suitable for other uses (e.g., pulp and paper production) and biomass that is not used commercially (Smeets & Faaij, 2007; Chum *et al.*, 2011). The resource potential depends on both environmental and socio-economic factors. For example, the change in forest management and harvesting regimes due to bioenergy demand depends on forest ownership, economic incentives and the structure of the associated forest industry. Also, the forest productivity and C-stock-response to changes in forest management and harvesting depend on the character of the forest ecosystem, as shaped by historic forest management and events such as fires, storms and insect outbreaks, but also on the management scheme, e.g., including replanting after harvest, soil protection, recycling of nutrients and soil types (Berndes *et al.*, 2013; Jonker *et al.*, 2013; Lamers *et al.*, 2013). In particular, optimizing forest management for mitigation is a complex issue with many uncertainties and still subject to scientific debate (see section GHG emission estimates of bioenergy production systems).

Organic wastes include waste from households and restaurants, discarded wood products such as paper, construction, and demolition wood waste, and waste waters suitable for anaerobic biogas production (Gregg & Smith, 2010; Haberl *et al.*, 2010). Organic waste may be dispersed and heterogeneous in quality but the health and environmental gains from collection and proper management through combustion or anaerobic digestion can be significant. Competition with alternative uses of the wastes may limit this resource potential.

Dedicated biomass plantations include annual (cereals, oil- and sugar crops) and perennial plants (e.g., switchgrass, Miscanthus) and tree plantations including both coppice and single-stem plantations (e.g., willow, poplar, eucalyptus, pine) (Hoogwijk *et al.*, 2005, 2009; Smeets *et al.*, 2007; Van Vuuren *et al.*, 2009; Dornburg *et al.*, 2010; Wicke *et al.*, 2011a). The range of estimates of technical bioenergy potentials from that resource in 2050 is particularly large (<50 to >500 EJ yr^{-1}). Technical bioenergy potentials from dedicated biomass plantations are generally calculated by multiplying (i) the area deemed available for energy crops by (ii) the yield per unit area and year (Batidzirai *et al.*, 2012; Coelho *et al.*, 2012). Some studies have identified a sizable technical potential (up to 100 EJ yr^{-1}) for bioenergy production using marginal and degraded lands (e.g., saline land) that are currently not in use for crop production or grazing (Nijsen *et al.*, 2012). However, how much land is really unused and available is contested (Erb *et al.*, 2007; Haberl *et al.*, 2010, 2011; Coelho *et al.*, 2012; Dauber *et al.*, 2012). Contrasting views on future technical bioenergy potentials from dedicated biomass plantations can be explained by differences in assumptions regarding feasible future agricultural crop yields, diet shifts, livestock feeding efficiency, land availability for energy crops and yields of energy crops (Dornburg *et al.*, 2010; Batidzirai *et al.*, 2012; Erb *et al.*, 2012). Many scientists agree that increases in food crop yields and higher feeding efficiencies and lower consumption of animal products would result in higher technical bioenergy potential.

Reduced traditional biomass demand

A substantial quantity of biomass will become available for modern applications by improving the end-use efficiency of traditional biomass consumption for energy, mostly in households but also within small industries (such as charcoal kilns, brick kilns, etc.). Traditional bioenergy represents approximately 15% of total global energy use and 80% of current bioenergy use (≈35 EJ yr^{-1}) and helps meeting the cooking and heating needs of ~2.7 billion people (Chum *et al.*, 2011). Cooking is the dominant end use; it is mostly done in open fires and rudimentary stoves, with approximately 10–20% conversion efficiency, leading to very high primary energy consumption. Advanced woodburning and biogas stoves can potentially reduce biomass fuel consumption by 60% or more (Jetter *et al.*, 2012) and further reduce CO_2 emissions, and in many cases black

carbon emissions, by up to 90% (Anenberg et al., 2013). Assuming that actual savings reach on average from 30% to 60% of current consumption, the total bioenergy potential from reducing traditional bioenergy demand can be estimated at 8–18 EJ yr^{-1}. An unknown fraction of global traditional biomass is consumed in a nonenvironmentally sustainable way, leading to forest degradation and deforestation. Detailed country studies have estimated the fraction of nonrenewable biomass from traditional bioenergy use to vary widely – e.g., from 1.6% for the Democratic Republic of Congo to 73% for Burundi (UNFCCC-CDM, 2012) – with most countries in the range between 10–30% (i.e., meaning that 70–90% of total traditional bioenergy use is managed sustainably). If that biomass could be saved through better technology, this would help restoring local ecosystems" (HH).

Bioenergy technologies

Conversion technologies

Numerous conversion technologies can transform biomass to heat, power, liquid and gaseous fuels for use in the residential, industrial, transport and power sectors (Chum et al., 2011 and GEA, 2012; Edenhofer et al., 2013; Fig. 2 for the pathways concerning liquid and gaseous fuels). Since SRREN, the major advances in the large-scale production of bioenergy include the increasing use of hybrid biomass-fossil fuel systems. For example,

the use of current commercial coal and biomass cocombustion technologies belong to the lowest cost technologies to implement renewable energy policies, enabled by the large-scale pelletized feedstocks trade (REN21, 2013; Junginger et al., 2014). Using biomass for combined power and heat, either cofired with coal or not, coupled to a network of district heating (to avoid cooling energy losses) and biochemical processing of waste biomass, are among the most cost-efficient and effective biomass applications for GHG emission reduction (Sterner & Fritsche, 2011).

Integrated gasification combined cycle (IGCC) technologies for coproduction of electricity and liquid fuels from coal and biomass with higher efficiency than current commercial processes are in demonstration phase to reduce cost (GEA, 2012; Larson et al., 2012). Coupling of biomass and natural gas for fuels is another option for liquid fuels (Baliban et al., 2013) as the biomass gasification technology development progresses. Simulations suggest that integrated gasification facilities are technically feasible (with up to 50% biomass input) (Meerman et al., 2011) and economically attractive with a CO_2 price of about 50€/tCO_2 (Meerman et al., 2012).

Many pathways and feedstocks can lead to biofuels for aviation (Fig. 2). The development of biofuel standards enabled domestic and transatlantic flights testing of 50% biofuel in jet fuel (REN21, 2012, 2013). Advanced 'drop in' fuels, such as iso-butanol, synthetic aviation kerosene from biomass gasification or upgrading of pyrolysis liquids, can be derived through a number of
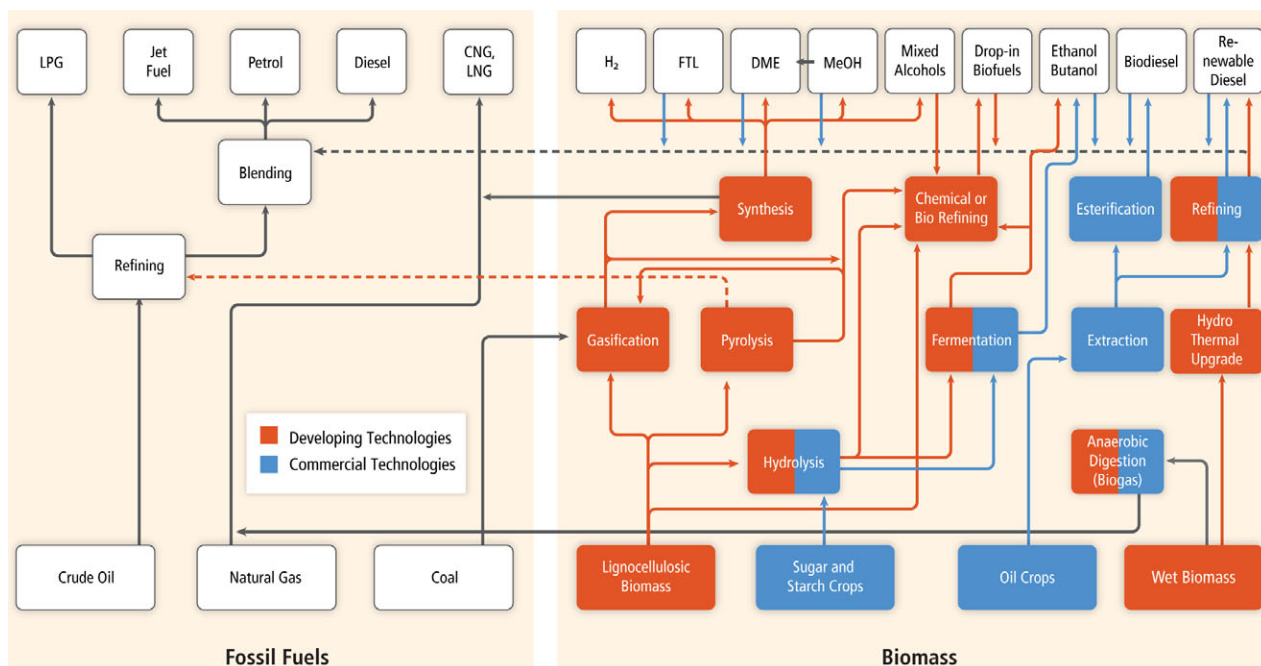
Fig. 2 Production pathways to liquid and gaseous fuels from biomass and, for comparison from fossil fuels (adapted from Turkenburg et al., 2012; GEA, 2012, Chapter 11).

possible conversion routes such as hydro treatment of vegetable oils, iso-butanol, and Fischer-Tropsch synthesis from gasification of biomass (Hamelinck & Faaij, 2006; Bacovsky *et al.*, 2010; Meerman *et al.*, 2011, 2012; Rosillo-Calle *et al.*, 2012). In most cases, powering electric cars with electricity from biomass has higher land-use efficiency and lower GWP effects than the usage of bioethanol from biofuel crops for road transport across a range of feedstocks, conversion technologies, and vehicle classes (Campbell *et al.*, 2009; Schmidt *et al.*, 2011), though costs remain a barrier (Schmidt *et al.*, 2011; Van Vliet *et al.*, 2011a,b).

The number of routes from biomass to a broad range of biofuels, shown in Fig. 2, includes hydrocarbons connecting today's fossil fuels industry in familiar thermal/catalytic routes such as gasification (Larson *et al.*, 2012) and pyrolysis (Bridgwater, 2012; Elliott, 2013; Meier *et al.*, 2013). In addition, advances in genomic technology and the integration between engineering, physics, chemistry, and biology points to new approaches in biomass conversion (Liao & Messing, 2012), such as biomolecular engineering (Li *et al.*, 2010; Peralta-Yahya *et al.*, 2012; Favaro *et al.*, 2013; Lee *et al.*, 2013; Yoon *et al.*, 2013). Advances in (bio)-catalysis and basic understanding of the synthesis of cellulose indicate alternative conversion pathways for fuels and chemicals under mild conditions (Serrano-Ruiz *et al.*, 2010; Carpita, 2012; Shen *et al.*, 2013; Triantafyllidis *et al.*, 2013; Yoon *et al.*, 2013).

Beccs

Bioenergy coupled with CO_2 Capture and Storage (BECCS) (Spath & Mann, 2004; Liu *et al.*, 2010, 2011) can mitigate climate change through negative emissions if CCS can be successfully deployed (Lenton & Vaughan, 2009; Cao & Caldeira, 2010). BECCS features prominently in long-run mitigation scenarios for two reasons: (i) The potential for negative emissions may allow shifting emissions in time; and (ii) Negative emissions from BECCS can compensate for residual emissions in other sectors (most importantly transport) in the second half of the 21st century. As illustrated in Fig. 3, BECCS is markedly different than fossil CCS because it not only reduces CO_2 emissions by storing C in long term geological sinks, but it continually sequesters CO_2 from the air through regeneration of the biomass resource feedstock (depending on the accounting framework, see section GHG emission estimates of bioenergy production systems).

BECCS deployment is in the development and exploration stages. The most relevant BECCS project is the Illinois Basin – Decatur Project (IBDP) that is projected to store 1 Mt CO_2 yr^{-1} (Gollakota & McDonald, 2012; Senel & Chugunov, 2013). In the US, two ethanol fuel production facilities are currently integrated commercially with carbon dioxide capture, pipeline transport, and use in enhanced oil recovery in nearby facilities at a rate of about 0.2 Mt CO_2 yr^{-1} (DiPietro *et al.*, 2012). Altogether there are 16 global BECCS projects in the exploration stage (Karlsson & Byström, 2011).

Critical to overall CO_2 storage is the realization of a lignocellulosic biomass supply infrastructure for large-scale commodity feedstock production and efficient advanced conversion technologies at scale; both benefit from cost reductions and technological learning as does the integrated system with CCS, with financial and institutional conditions that minimize the risks of investment and facilitate dissemination (Eranki & Dale, 2011; IEA, 2012, 2013). Integrated analysis is needed to capture system and knock-on effects for bioenergy potentials (IEA, 2013). A nascent feedstock infrastructure for densified biomass trading globally could indicate decreased pressure on the need for closely colocated storage and production (IEA, 2011; Junginger *et al.*, 2014). However, bioenergy products commonly have lower energy density than their fossil alternatives and supply chains may be associated with higher GHG emissions.

Koornneef *et al.* (2012, 2013) estimate the overall technical potential to be around 10Gt CO_2 storage per year for both IGCC-CCS cofiring (i.e., Integrated Gasification Combined Cycle with cogasification of biomass), and BIGCC-CCS (Biomass Integrated Gasification Combined Cycle), and around 6 Gt CO_2 storage for FT diesel (i.e., Biodiesel based on gasification and Fischer–Tropsch synthesis), and 2.7 Gt CO_2 for biomethane production. McLaren (2012) estimates the potential capacity (similar to technical potential) to be between 2.4 and 10 Gt CO2 per year for 2030–2050. The economic potential, at a CO_2 price of around 70$/tCO2 is estimated to be around 3.3 Gt CO2, 3.5 Gt CO2, 3.1 Gt CO2 and 0.8 Gt CO2 in the corresponding four cases, judged to be those with highest economic potential (Koornneef *et al.*, 2012, 2013). Potentials are assessed on a route-by-route basis and cannot simply be added, as they may compete and substitute each other. Practical figures might be not much higher than 2.4 Gt CO_2 per year at 70–250$/tCO$_2$ (McLaren, 2012). Altogether, until 2050 the economic potential is anywhere between 2 and 10 Gt CO_2 per year. Some climate stabilization scenarios project considerable higher deployment toward the end of the century, even in some 580–650 ppm scenarios, operating under different time scales, socio-economic assumptions, technology portfolios, CO_2 prices, and interpreting BECCS as part of an overall mitigation framework (e.g., Rose *et al.*, 2012; Kriegler *et al.*, 2013; Tavoni & Socolow, 2013).

Key point 2: The economic potential of BECCS is uncertain but could lie in the range of 2–10 Gt CO_2 per year in 2050.
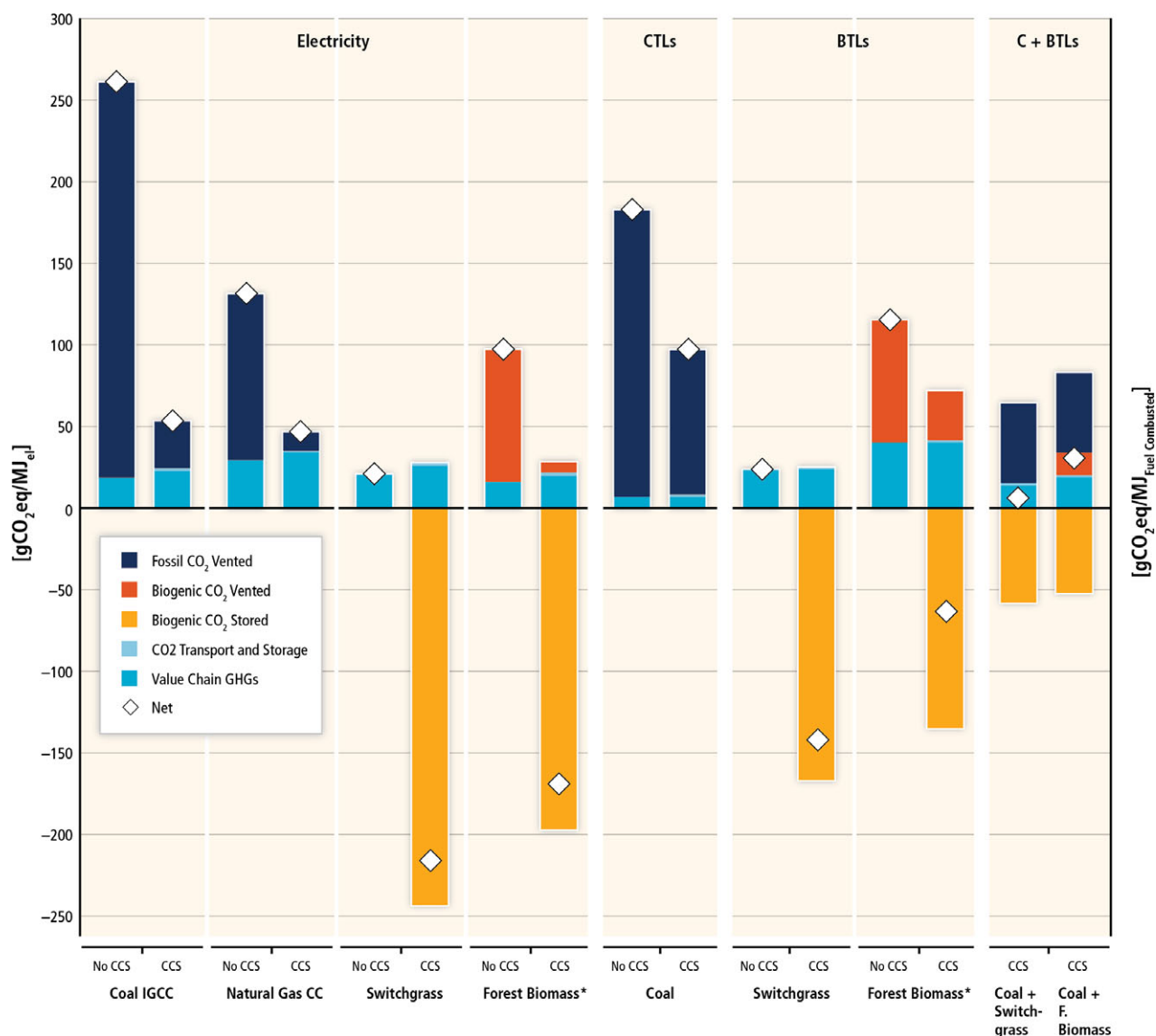
Fig. 3 Illustration of the sum of CO_2-equivalent (GWP$_{100}$: Global Warming Potential over 100 years) emissions from the process chain of alternative transport and power generation technologies both with and without CCS. Values are uncertain and depend on the production chain as well as what and how biomass is sourced. Differences in C-density between forest biomass and switchgrass are taken into account but not calorific values (balance-of-plant data are for switchgrass, Larson *et al.*, 2012). Estimated emissions vary with biomass feedstock and conversion technology combinations, as well as life-cycle GHG calculation boundaries. For policy relevant purposes, counterfactual and market-mediated aspects (e.g., indirect land use change: ILUC), changes in soil organic carbon, or changes in surface albedo need also to be considered, possibly leading to significantly different outcomes (Section GHG emission estimates of bioenergy production systems, Figs 4 and 5). Units: g-CO_2-eq. MJ$_{EI}$ (left *y*-axis, electricity); g-CO_2-eq. MJ^{-1} combusted (right *y*-axis, transport fuels). Direct CO_2 emissions from energy conversion ('vented' and 'stored') are adapted from the mean values in Tables 12.7, 12.8, and 12.15 of reference (1), which are based on the work of references (2, 3), and characterized with the emission metrics in reference (4). Impacts upstream in the supply chain associated with feedstock procurement (i.e., sum of GHGs from mining/cultivation, transport, etc.) are adapted from references (5, 6) and Fig. 4 (mean values). (1) Larson *et al.*, 2012; (2) Woods *et al.*, 2007; (3) Liu *et al.*, 2010; (4) Guest *et al.*, 2013; (5) Turconi *et al.*, 2013; (6) Jaramillo *et al.*, 2008).

Possible climate risks of BECCS relate to reduction of land carbon stock, feasible scales of biomass production and increased N_2O emissions, and potential leakage of CO_2 stored in deep geologic reservoirs (Rhodes & Keith, 2008). The assumptions of sufficient spatially appropriate CCS capture, pipeline and storage infrastructure are uncertain. The literature highlights that BECCS as well as CCS deployment is dependent on strong financial incentives, as they are not cost competitive otherwise.

Figure 3 illustrates some GHG effects associated with BECCS pathways. Trade-offs between CO_2 capture rate and feedstock conversion efficiency are possible. Depending on the feedstock, technology, and energy product, energy penalties with CCS span ~10–20% (Liu *et al.*, 2011; Larson *et al.*, 2012). Depicted are pathways with the highest removal rate but not necessarily with the highest feedstock conversion rate. Among all BECCS pathways, those based on integrated gasification combined cycle produce most significant geologic storage potential from biomass, alone (shown in Fig. 4, electricity) or coupled with coal. Fischer-Tropsch diesel fuel production with biomass as feedstock and CCS attached to plant facilities could enable BECCS for transport; uncertainties in input factors and output metrics warrant further research (Van Vliet *et al.*, 2009); Fischer-Tropsch diesel would also allow net removal but at lower rates than BIGCC.

Microalgea and cellulosic biofuels

Microalgae offer an alternative to land-based bioenergy. Its high-end technical potential might be compromised by water supply, if produced in arid land, or by its
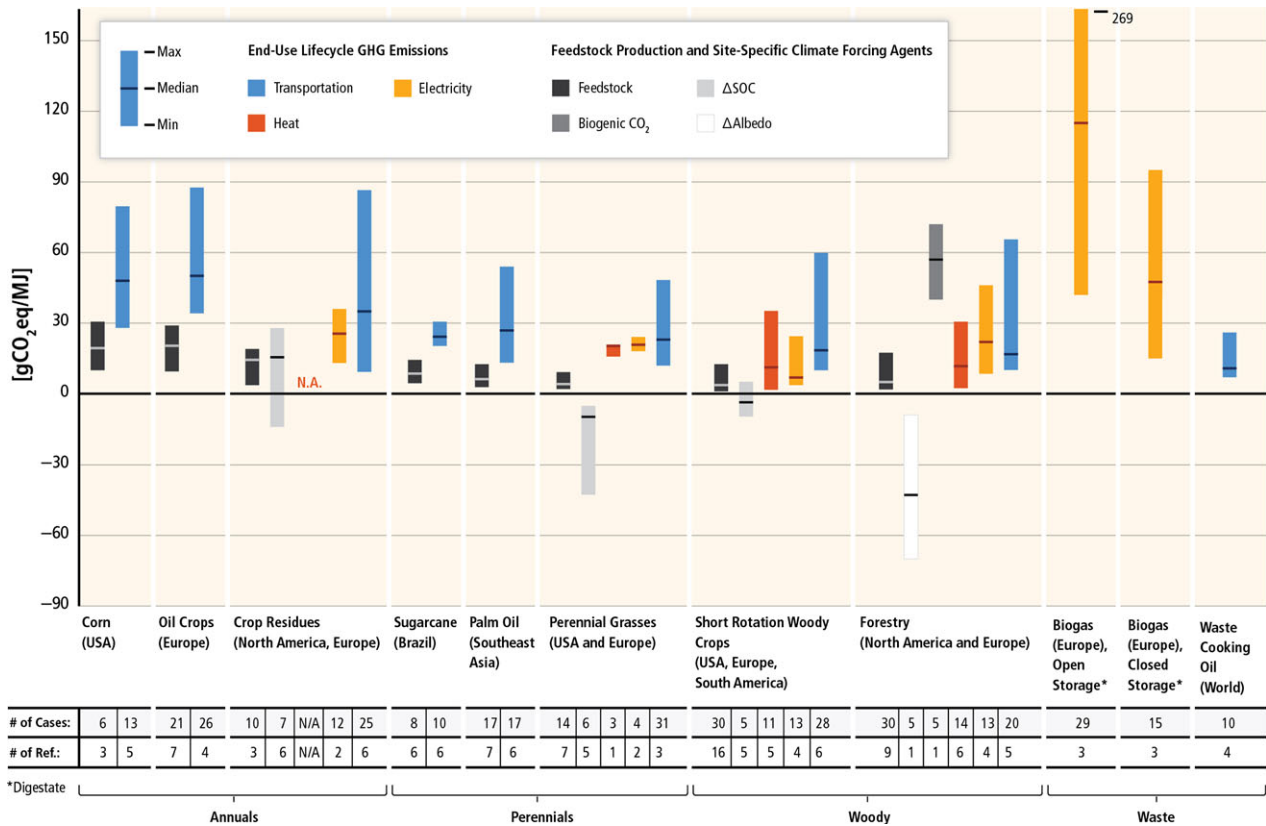

Fig. 4 The sum of CO_2-equivalent (GWP100) emissions from the process chain of major bioenergy product systems, not including emissions from market-mediated effects such as land-use change (see Fig. 5). The interpretation of values depends also on baseline assumption about the land carbon sink when appropriate and the intertemporal accounting frame chosen, and should also consider information from Fig. 5. The lower and upper bounds of the bars represent the minimum and the maximum value reported in the literature. Whenever possible, only peer-reviewed scientific literature published post SRREN is used (but results are comparable). Note that narrow ranges may be an artifact of the number of studies for a given case. Results are disaggregated in a manner showing the impact of *Feedstock* production (in g CO_2-eq. MJ^{-1} LHV of feedstock) and the contributions from end product/conversion technology. Results from conversion into final energy products *Heat*, *Power*, and *Transport fuels* include the contribution from *Feedstock* production and are shown in g CO_2-eq. MJ^{-1} of final product. For some pathways, additional site-specific climate forcing agents apply and are presented as separate values to be added or subtracted from the value indicated by the mean in the *Feedstock* bar (green). Final products are also affected by these factors, but this is not displayed here. References are provided in Table S1. Note that the biofuels technologies for transport from lignocellulosic feedstocks, short rotation woody crops, and crop residues, including collection and delivery, are developing so larger ranges are expected than for more mature commercial technologies such as sugarcane ethanol and WCO biodiesel. The biogas electricity bar represents scenarios using LCAs to explore treating mixtures of a variety of lignocellulosic feedstocks (e.g., ensiled grain or agricultural residues or perennial grasses) with more easily biodegradable wastes (e.g., from animal husbandry), to optimize multiple outputs. Variations in CH_4 leakage of biogas systems leads to a broad range of life-cycle emissions.

impact on ocean ecosystems. To make algae cost competitive, maximizing algal lipid content (and then maximizing growth rate) require essential technological breakthroughs (Davis *et al.*, 2011; Sun *et al.*, 2011; Jonker & Faaij, 2013). Its market potential depends on the co-use of products for food, fodder, higher value products, and on fuel markets (Chum *et al.*, 2011).

Similarly, lignocellulosic feedstocks produced from waste or residues, or grown on land unsupportive of food production (e.g., contaminated land for remediation as in previously mined land) have been suggested to reduce socio-environmental impact. In addition, lignocellulosic feedstocks can be bred specifically for energy purposes, and can be harvested by coupling collection and preprocessing (densification and others) in depots prior to final conversion, which could enable delivery of more uniform feedstocks throughout the year (Eranki & Dale, 2011; US DOE, 2011; Argo *et al.*, 2013). Various conversion pathways are in R&D, near commercialization, or in early deployment stages in several countries (see 2.6.3 in Chum *et al.*, 2011). Crops suitable for cultivation on marginal land can compete with food crops unless land prices rise to make cultivation on marginal land preferable, i.e., land-use competition can still arise. Depending on the feedstock, conversion process, prior land use, and land demand, lignocellulosic bioenergy can be associated with high or low GHG emissions (e.g., Davis *et al.*, 2012).

Cookstoves

Substantial progress has also been achieved in the last 4 years in small-scale bioenergy applications in the areas of technology innovation, impact evaluation and monitoring and in large-scale implementation programs. Advanced combustion biomass cookstoves reduce fuel use by more than 60% and hazardous pollutant as well as short-lived climate pollutants by up to 90% (Kar *et al.*, 2012; Anenberg *et al.*, 2013). Innovative designs include micro-gasifiers, stoves with thermoelectric generators to improve combustion efficiency and provide electricity to charge LED lamps while cooking, stoves with advanced combustion chamber designs and multi-use stoves (e.g., cooking and water heating for bathing) (Ürge-Vorsatz *et al.*, 2012; Anenberg *et al.*, 2013). Biogas stoves, in addition to providing clean combustion, help reduce the health risks associated to the disposal of organic wastes. There has also been a boost in cookstove dissemination efforts ranging from regional (multicountry) initiatives (Wang *et al.*, 2013) to national, and project level interventions. In total more than 200 cookstove large-scale projects are in place worldwide, with several million efficient cookstoves installed each year (Cordes, 2011). A Global Alliance for

Clean Cook stoves has been launched that is promoting the adoption of 100 million clean and efficient cookstoves per year by 2030 and several countries have launched National Cookstove Programs in recent years (e.g., Mexico, Peru, Honduras, and others). Many cookstove models are now manufactured in large-scale industrial facilities using state-of-the-art materials and combustion design technology. Significant efforts are also in place to develop international standards and regional stove testing facilities. In addition to providing tangible local health and other sustainable benefits, replacing traditional open fires with efficient biomass cookstoves has a global mitigation potential estimated in between 0.6 and 2.4 Gt CO_2-eq yr^{-1} (Ürge-Vorsatz *et al.*, 2012). Small-scale decentralized biomass power generation systems based on biomass combustion and gasification and biogas production systems have the potential to meet the electricity needs of rural communities in the developing and developed countries alike. The biomass feedstocks for these small-scale systems could come from residues of crops and forests, wastes from livestock production and/or from small-scale energy plantations (Faaij, 2006).

Key point 3: Advanced combustion biomass cookstoves reduce fuel use by more than 60% and hazardous pollutant as well as short-lived climate pollutants by up to 90%.

GHG emission estimates of bioenergy production systems

The combustion of biomass generates gross GHG emissions roughly equivalent to those from combustion of fossil fuels. If bioenergy production is to generate a net reduction in emissions, it must do so by offsetting those emissions through increased net carbon uptake of biota and soils. The appropriate comparison is then between the net biosphere flux in the absence of bioenergy compared to the net biosphere flux in the presence of bioenergy production. Direct and indirect effects need to be considered in calculating these fluxes.

Bioenergy systems directly influence local and global climate through: (i) GHG emissions from fossil fuels associated with biomass production, harvest, transport, and conversion to secondary energy carriers (Von Blottnitz & Curran, 2007; Van der Voet *et al.*, 2010); (ii) CO_2 and other GHG emissions from biomass or biofuel combustion (Cherubini *et al.* 2011); (iii) atmosphere-ecosystem exchanges of CO_2 following land disturbance (Berndes *et al.*, 2013; Haberl, 2013); (iv) non-CO_2 GHG emissions of short-lived GHGs like black carbon and other chemically active gases (NO_x, CO, etc.) (Jetter *et al.*, 2012; Tsao *et al.*, 2012) and non-CO_2 GHGs from

land management and perturbations to soil biogeo-chemistry, e.g., N_2O from fertilizers, and CH_4 (Cai *et al.*, 2001); (v) climate forcing resulting from alteration of biophysical properties of the land surface affecting the surface energy balance (e.g., from changes in surface albedo, heat and water fluxes, surface roughness, etc.) (Bonan, 2008; West *et al.*, 2010; Pielke *et al.*, 2011). Market-mediated 'indirect' effects include the partial or complete substitution of fossil fuels and the indirect transformation of land use by equilibrium effects. Hence, the total climate forcing of bioenergy depends on feedstock, site-specific climate and ecosystems, management conditions, production pathway, end use, and on the interdependencies with energy and land markets.

Bioenergy systems have often been assessed (e.g., in LCA studies, integrated assessment models, policy directives) under the assumption that the CO_2 emitted from biomass combustion is climate neutral because the carbon that was previously sequestered from the atmosphere is returned to the atmosphere in combustion if the bioenergy system is managed sustainably (Chum *et al.*, 2011; Creutzig *et al.*, 2012a,b). The neutrality perception is linked to a misunderstanding of the guidelines for GHG inventories, e.g., IPCC – Land Use, Land-Use Change and Forestry (2000) states 'Biomass fuels are included in the national energy and carbon dioxide emissions accounts for informational purposes only. Within the energy module biomass consumption is assumed to equal its regrowth. Any departures from this hypothesis are counted within the Land Use Change and Forestry Model.' Carbon neutrality is valid if the countries account for LUC in their inventories for self-produced bioenergy. The shortcomings of this assumption have been extensively discussed (Haberl, 2013; Searchinger, 2010; Searchinger *et al.*, 2009; Cherubini *et al.* 2011).

Studies also call for a consistent and case-specific carbon-stock/flux change accounting that integrates the biomass system with the global carbon cycle (Mackey *et al.*, 2013). As shown in the Working Group I of the AR5 (Myhre & Shindell, 2013) and elsewhere (Plattner *et al.*, 2009; Fuglestvedt *et al.*, 2010), the climate impacts can be quantified at different points along a cause-effect chain, from emissions to changes in temperature and sea level rise. While a simple sum of the net CO_2 fluxes over time can inform about the skewed time distribution between sources and sinks ('C debt') (Marland & Schlamadinger, 1995; Fargione *et al.*, 2008; Bernier & Paré, 2013), understanding the climate implications as it relates to policy targets (e.g., limiting warming to 2 °C) requires models and/or metrics that also include temperature effects and climate consequences (Tanaka *et al.*, 2013). While the warming from fossil fuels is nearly

permanent as it persists for thousands of years, direct impacts from renewable bioenergy systems cause a perturbation in global temperature that is temporary and even at times leads to cooling if terrestrial carbon stocks are not depleted (House *et al.*, 2002; Cherubini *et al.*, 2013; Joos *et al.*, 2013; Mackey *et al.*, 2013). For example, in the specific case of existing forests that may continue to grow if not used for bioenergy, some studies employing counterfactual baselines show that forest bioenergy systems can have higher cumulative CO_2 emissions than a fossil reference system (for a time period ranging from few decades up to several centuries) (Pingoud *et al.*, 2012; Bernier & Paré, 2013; Guest *et al.*, 2013; Holtsmark, 2013). In some cases, cooling contributions from changes in surface albedo can mitigate or offset these effects (Anderson-Teixeira *et al.*, 2012; Arora & Montenegro, 2011; O'Halloran *et al.*, 2012; Hallgren *et al.*, 2013).

Accounting always depends on the spatial and temporal system boundaries adopted when assessing climate change impacts, and the assumed baseline, and hence includes value judgements (Schwietzke *et al.*, 2011; Cherubini *et al.*, 2013; Kløverpris & Mueller, 2013).

Two specific contributions to the climate forcing of bioenergy, not addressed in detail in SRREN include nitrous oxide and biogeophysical factors.

Nitrous oxide (N_2O) emissions

for first-generation crop-based biofuels, as with food crops, emissions of N_2O from agricultural soils is the single largest contributor to direct GHG emissions, and one of the largest contributors across many biofuel production cycles (Smeets *et al.*, 2009; Hsu *et al.*, 2010). Emission rates can vary by as much as 700% between different crop types for the same site, fertilization rate and measurement period (Kaiser & Ruser, 2000; Don *et al.*, 2012; Yang *et al.*, 2012). In some locations, N_2O emissions can so high that some biofuel systems that are expected to deliver significant GHG savings can cause higher GHG emissions than the fossil fuels displaced (Smith *et al.*, 2012b). Improvements in nitrogen use efficiency and nitrogen inhibitors can substantially reduce emissions of N_2O (Robertson & Vitousek, 2009). For some specific crops, such as sugarcane, N_2O emissions can be low (Macedo *et al.*, 2008; Seabra *et al.*, 2011) or high (Lisboa *et al.*, 2011). Some bioenergy crops require relatively limited N input and can reduce GHG emissions relative to the former land use where they replace conventional food crops (Clair *et al.*, 2008).

Biogeophysical factors

Land cover changes or land-use disturbances of the surface energy balance, such as surface albedo, surface

roughness, and evapotranspiration influence the climate system (Betts, 2001, 2007; Marland *et al.*, 2003; Bonan, 2008; Jackson *et al.*, 2008). Perturbations to these can lead to both direct and indirect climate forcings whose impacts can differ in spatial extent (global and/or local) (Bala *et al.*, 2007; Davin *et al.*, 2007). Surface albedo is found to be the dominant direct biogeophysical climate impact mechanism linked to land cover change at the global scale, especially in areas with seasonal snow cover (Claussen *et al.*, 2001; Bathiany *et al.*, 2010), with radiative forcing effects possibly stronger than those of the cooccuring C-cycle changes (Randerson *et al.*, 2006; Lohila *et al.*, 2010; Bright *et al.*, 2011; O'Halloran *et al.*, 2012). Land cover changes can also affect other biogeophysical factors like evapotranspiration and surface roughness, which can have important local (Georgescu *et al.*, 2011; Loarie *et al.*, 2011) and global climatic consequences (Bala *et al.*, 2007; Swann *et al.*, 2010, 2011). Biogeophysical climate impacts from changes in land use are site specific and show variations in magnitude across different geographic regions and biomes (Bonan, 2008; Jackson *et al.*, 2008; Anderson *et al.*, 2011; Betts, 2011; Arora & Montenegro, 2011; Anderson-Teixeira *et al.*, 2012; Pielke *et al.*, 2011).

Key point 4: Assessing land-use mitigation options should include evaluating biogeophysical impacts, such as albedo modifications, as their size may be comparable to impacts from changes to the C cycle.

Attributional life-cycle impacts

Figure 4 illustrates the range of life-cycle global direct climate impact (in g CO_2 equivalents per MJ, after characterization with GWP time horizon = 100 years) attributed to major global bioenergy products reported in the peer-reviewed literature after 2010. Results are broadly comparable to those of Chapter 2 in SRREN (Figure 2.10 and 2.11 in SRREN; those figures displayed negative emissions, resulting from crediting emission reduction due to substitution effects; this article does not allocate credits to feedstocks to avoid double accounting). Significant variation in the results reflects the wide range of conversion technologies and their reported performances in addition to analyst assumptions affecting system boundary completeness, emission inventory completeness, and choice of allocation method (among others).

Additional 'site-specific' land-use considerations such as changes in soil organic carbon stocks ('ΔSOC'), changes in surface albedo ('Δalbedo'), and the skewed time distribution of terrestrial biogenic CO_2 fluxes can either reduce or compound land-use impacts and are presented to exemplify that, for some bioenergy

systems, these impacts can be greater in magnitude than life-cycle impacts from feedstock cultivation and bioenergy product conversion. 'Site-specific' land-use considerations are geographically explicit and highly sensitive to background climate conditions, soil properties, biomass yields, and land management regimes. The figure reveals that studies find very different values depending on the boundaries of analysis chosen, site-specific effects and management methods. Site-specific characteristics, perspectives on spatial and time scale as well as initial conditions, will generally affect the results together with the choice of climate metrics applied.

Key point 5: Fuels from sugarcane, perennial grasses, crop residues and waste cooking oil and many forest products have lower attributional life-cycle emissions than other fuels, depending on N_2O emissions, fuel used in conversion process, forest carbon dynamics, and other site-specific factors and counterfactual dynamics (land-use change emissions can still be substantial, see Fig. 5).

Another important result is that albedo effects and site-specific CO_2 fluxes are highly variable for different forest systems and environmental conditions and determine the total climate forcing of bioenergy from forestry.

Direct land-use change

Direct land-use change (LUC) occurs when bioenergy crops displace other crops, pastures or forests, while ILUC results from bioenergy deployment triggering the conversion to cropland or pasture of lands, somewhere on the globe, to replace a fraction of the displaced crops (Delucchi, 2010; Hertel *et al.*, 2010; Searchinger *et al.*, 2008). Direct LUC to establish biomass cropping systems can increase net GHG emissions, for example if carbon rich ecosystems such as wetlands, forests or natural grasslands are brought into cultivation (Chum *et al.*, 2011; Gibbs *et al.*, 2008; UNEP, 2009). Biospheric C losses associated with LUC from some bioenergy schemes can be, in some cases, more than hundred times larger than the annual GHG savings from the assumed fossil fuel replacement (Chum *et al.*, 2011; Gibbs *et al.*, 2008). Impacts have been shown to be significantly reduced when a dynamic baseline includes future trends in global agricultural land use (Kløverpris & Mueller, 2013; this study accounts for 100 years, not for 30 years as e.g., in Searchinger *et al.*, 2008). Albeit at lower magnitude, beneficial direct LUC effects can also be observed, for example when some perennial grasses or woody plants replace annual crops grown with high fertilizer input, or where such plants are produced on lands with carbon-poor soils (Harper *et al.*, 2010;
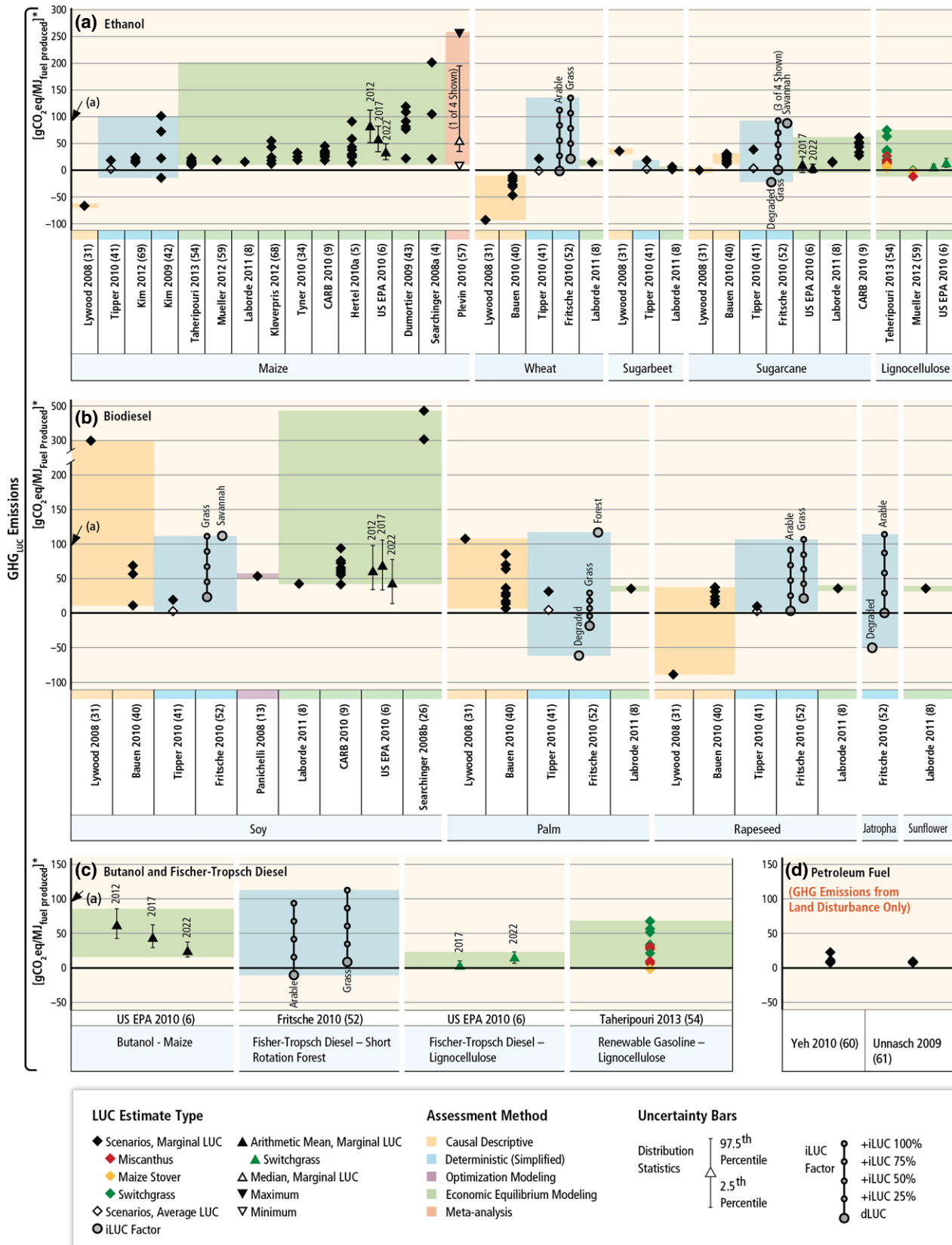
Sochacki *et al.*, 2012; Sterner & Fritsche, 2011; Tilman *et al.*, 2006) (Brandão *et al.*, 2011), including degraded lands (Wicke *et al.*, 2008, 2011a) and marginal croplands where cultivation of annual food/feed crops is not economically viable and where planting of bioenergy feedstock is less likely to cause ILUC (Gelfand *et al.*, 2013).

A range of agro-ecological options to improve agricultural practices such as no/low tillage conservation, and agroforestry have potential to increase yields (e.g., in sub-Saharan Africa), while also providing a range of co-benefits such as increased soil organic matter. Such options require a much lower level of investment and inputs and are thus more readily applicable in developing countries, while also holding a low risk of increased GHG emissions (Keating *et al.*, 2013).

Bioenergy from forests

In large managed forest estates, management activities in one stand are coordinated with activities elsewhere in the landscape with the purpose to provide a steady flow of harvested wood. While carbon stock decreases in stands that are harvested, carbon stock increases in other stands resulting in landscape-level carbon stock that fluctuates around a trend line that can be increasing or decreasing, or remain roughly stable (Berndes *et al.*, 2013; Hudiburg *et al.*, 2011; Lundmark *et al.*, 2014). Changes in the management of forests to provide biomass for energy can result in both losses and gains in forest carbon stocks, which are determined by the dynamics of management operations and natural biotic and abiotic forces (Cherubini *et al.*, 2012; Hudiburg *et al.*, 2011; Lundmark *et al.*, 2014). Bioenergy implementation may also affect other forest based industry sectors (e.g., building sector, pulp and paper, panel industry), which can provide favorable climate mitigation benefits (Lippke *et al.*, 2011; Pingoud *et al.*, 2012; Ximenes *et al.*, 2012).

Carbon and GHG balances also depends on policy formulation, e.g., restricted feedstock eligibility on bioenergy markets can reduce the GHG reduction benefits (Daigneault *et al.*, 2012; Latta *et al.*, 2013).

The design of the assessment framework has a strong influence on the calculated carbon balance (Berndes *et al.*, 2013; Lamers & Junginger, 2013). Carbon accounting at the stand level that start the accounting when biomass is harvested for bioenergy naturally finds upfront carbon losses that is found to delay net GHG savings up to several decades (carbon debt, e.g., Pingoud *et al.*, 2012). Assessments over larger landscapes report both forest carbon gains (Lundmark *et al.*, 2014) and losses delaying the GHG reduction benefit (Latta *et al.*, 2013; McKechnie *et al.*, 2011), as well as reductions in forest sink strength (foregone carbon sequestration) reducing or even outweighing for some period of time the GHG emissions savings from displacing fossil fuels (Haberl *et al.*, 2012; Holtsmark, 2012; Hudiburg *et al.*, 2011).

Intensive forest management activities of the early- to mid-20th century as well as other factors such as recovery from past overuse, have led to strong forest C-sinks in many OECD regions (Erb *et al.*, 2013; Loudermilk *et al.*, 2013; Nabuurs *et al.*, 2013; Pan *et al.*, 2011). However, the sink capacity decreases as forests approach maturity (Körner, 2006; Nabuurs *et al.*, 2013; Smith, 2005). Climate change mitigation strategies needs to recognize the possible carbon sink/source function of growing forests and the full range of forest products including their fossil carbon displacement capacity and the timing of emissions when carbon is stored in forest products over varying time scales (Lippke *et al.*, 2011). Active management can in some forest landscapes promote further sequestration and provide a steady output of biomass for bioenergy and other forest products, resulting in continuous fossil substitution benefits also when the sink strength of the forest eventually saturates (Canadell & Raupach, 2008; Ciais *et al.*, 2008; Lundmark *et al.*, 2014; Nabuurs *et al.*, 2007, 2013).

The anticipation of positive market development for bioenergy and other forest products may promote changes in forest management practices and net growth in forest area, contributing to increased carbon stocks, but may cause ILUC (Sedjo & Tian, 2012) (Dale *et al.*, 2013; Eisenbies *et al.*, 2009). Conservation of high

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Fig. 5 Estimates of GHG$_{LUC}$ emissions – GHG emissions from biofuel production-induced LUC (as g CO$_2$eq MJ$_{fuel\ produced}^{-1}$) over a 30 year time horizon organized by fuel(s), feedstock, and study. Assessment methods, LUC estimate types and uncertainty metrics are portrayed to demonstrate the diversity in approaches and differences in results within and across any given category. Points labeled 'a' on the *y* axis represent a commonly used estimate of life-cycle GHG emissions associated with the direct supply chain of petroleum gasoline (frame a) and diesel (frame b) and Fischer-Tropsch diesel (frame c). For comparison the GHG emissions from land disturbances of petroleum fuels are also given (frame d). These emissions are not directly comparable to GHG$_{LUC}$ because the emission sources considered are different, but are potentially of interest for scaling comparison. Based on (Warner *et al.*, 2013). Please note: These estimates of global LUC are highly uncertain, unobservable, unverifiable, and dependent on assumed policy, economic contexts, and inputs used in the modeling. All entries are not equally valid nor do they attempt to measure the same metric despite the use of similar naming conventions (e.g., ILUC). In addition, many different approaches to estimating GHG$_{LUC}$ have been used. Therefore, each paper has its own interpretation and any comparisons should be made only after careful consideration. *CO$_2$eq includes studies both with and without CH$_4$ and N$_2$O accounting.

carbon-stock densities in old forests that are not at high risk of disturbance may be preferable to intensive management for wood output, while harvest of other mature forests that are at high risk of disturbance and have low productivity may be the best option, although involving an initial period (decades) of net losses in forest carbon (Nabuurs *et al.*, 2013).

In short, biomass that would otherwise be burned without energy recovery, rapidly decomposing residues and organic wastes can produce close to immediate GHG savings when used for bioenergy (Zanchi *et al.*, 2011), similarly to increasing the biomass outtake from forests affected by high mortality rates (Lamers *et al.*, 2013). When slowly decomposing residues are used and when changes in forest management to provide biomass for energy causes reductions in forest carbon stocks or carbon sink strength, the GHG mitigation benefits are delayed, sometimes many decades (Repo *et al.*, 2011). Conversely, when management changes in response to bioenergy demand so as to enhance the sink strength in the forest landscape, this improves the GHG mitigation benefit.

Indirect land-use change

Indirect land-use change is difficult to ascertain because the magnitude of these effects must be modeled (Nassar *et al.*, 2011) raising important questions about model validity and uncertainty (Gawel & Ludwig, 2011; Khanna *et al.*, 2011; Liska & Perrin, 2009; Plevin *et al.*, 2010; Wicke *et al.*, 2012) and about policy implications (DeCicco, 2013; Finkbeiner, 2013; Plevin *et al.*, 2013). Most available model-based studies have consistently found positive and, in some cases, high emissions from LUC and ILUC, mostly of first-generation biofuels, albeit with high variability and uncertainty in results (Warner *et al.*, 2013; see also Chen & Khanna, 2012; Creutzig & Kammen, 2010; Dumortier *et al.*, 2011; Havlík *et al.*, 2011; Hertel *et al.*, 2010; Taheripour *et al.*, 2011; Timilsina *et al.*, 2012) Causes of the large uncertainty include: incomplete knowledge of global economic dynamics (trade patterns, land-use productivity, diets, use of by-products, fuel prices and elasticities); selection of specific policies modeled; and the treatment of emissions over time (Khanna *et al.*, 2011; O'Hare *et al.*, 2009; Wicke *et al.*, 2012). In addition, LUC modeling philosophies, model structures, and features (e.g., dynamic vs. static models, partial vs. general equilibrium) differ among studies. Variations in estimated GHG emissions from biofuel-induced LUC are also driven by differences in scenarios assessed, varying assumptions, inconsistent definitions across models (e.g., LUC, land type), specific selection of reference scenarios against which (marginal) LUC is quantified, and disparities in data availability and quality. The general lack of thorough sensitivity and uncertainty analysis hampers the evaluation of plausible ranges of estimates of GHG emissions from LUC.

Key point 6: Land-use change associated with bioenergy implementation can have a strong influence on the climate benefit. Indirect land-use effects and other consequential changes are difficult to model and uncertain, but are nonetheless relevant for policy analysis.

Wicke *et al.* (2012) identified the need to incorporate the impacts of ILUC prevention or mitigation strategies in future modeling efforts, including the impact of zoning and protection of carbon stocks, selective sourcing from low risk areas, policies and investments to improve agricultural productivity, double cropping, agroforestry schemes and the (improved) use of degraded and marginal lands. ILUC is mostly assumed to be avoided in the modeled mitigation pathways of global stabilization scenarios. The relatively limited number of fuels covered in the literature precludes a complete set of direct comparisons across alternative and conventional fuels sought by regulatory bodies and researchers.

GHG emissions from LUC can be reduced, for instance through production of bioenergy coproducts that displace additional feedstock requirements thus decreasing the net area needed (e.g., for corn, Wang *et al.*, 2011; for wheat, Berndes *et al.*, 2011). Examples have been presented where the land savings effect of coproducts use as livestock feed more than outweigh the land claim of the bioenergy feedstock (Lywood *et al.*, 2009; Weightman *et al.*, 2011). Appropriate management of livestock and agriculture can lead to improved resource efficiency, lower GHG emissions and lower land use while releasing land for bioenergy or food production as demonstrated for Europe (De Wit *et al.*, 2013) and Mozambique (Van der Hilst *et al.*, 2012a).

Producing biofuels from wastes and sustainably harvested residues, and replacing first-generation biofuel feedstocks with lignocellulosic plants (e.g., grasses) may mitigate ILUC, especially if incentives exist for planting lignocellulosic plants on lands where cultivation of conventional food/feed crops is difficult (Davis *et al.*, 2012; Scown *et al.*, 2012). While ILUC quantifications remain uncertain, lower agricultural yields, land-intensive diets, and livestock feeding efficiencies, stronger climate impacts and higher energy crop production levels can result in higher LUC-related GHG emissions. But ILUC impacts can also be reduced (De Wit *et al.*, 2011, 2013; Fischer *et al.*, 2010; Rose *et al.*, 2013; Van Dam *et al.*, 2009a,b; Van der Hilst *et al.*, 2012a; Wicke *et al.*, 2009).

Key point 7: LUC impacts can be mitigated through: reduced land demand for food, fiber and bioenergy (e.g., diets, yields, efficient use of biomass, e.g., utilizing waste and residues); synergies between different land-use systems using adapted feedstocks (e.g., use hardy plants to cultivate degraded lands not suitable for conventional food crops); and governance systems and development models to protect ecosystems and promote sustainable land-use practices where land is converted to make place for biomass production.

Indirect effects are not restricted to indirect GHG effects of production of biomass in agricultural systems, but could also be relevant to bioenergy from wood sources. In addition, indirect effects could also apply to biodiversity threats, environmental degradation, and external social costs, which are not considered here (see sections Bioenergy and sustainable development and Trade-offs and synergies with land, water, food and biodiversity below). As with any other renewable fuel, bioenergy can replace or complement fossil fuel. When a global cap on CO_2 emissions is absent, the amount of displaced fossil fuels is highly uncertain, and depends on the relative price elasticities of supply and demand for fuels (Chen & Khanna, 2012; Drabik & De Gorter, 2011; Hochman *et al.*, 2010; Rajagopal *et al.*, 2011; Thompson *et al.*, 2011b).

Future potential deployment in climate mitigation scenarios

Climate mitigation scenarios are commonly explored in so-called Integrated Assessment Models. These models specify sets of technologies and explore cost-efficient mitigation options under various assumptions, for example with and without BECCS being available. These models consider the global economy in equilibrium and focus on timescales of up to 100 years. These models mostly report mitigation options assuming strong global governance, e.g., a price on GHG emissions. In the following, we report the results of these models.

In the IPCC SRREN scenarios, bioenergy is projected to contribute 80–190 EJ yr^{-1} to global primary energy supply by 2050 for 50% of the scenarios in the two climate mitigation levels modeled. The ranges were 20–265EJ yr^{-1} for the less stringent scenarios and 25–300 EJ for the tight climate mitigation scenarios (<440 ppm). Many of these scenarios coupled bioenergy with CCS. The GEA (2012) scenarios project 80–140 EJ by 2050, including extensive use of agricultural residues and second-generation bioenergy to try to reduce the adverse impacts on land use and food production, and the coprocessing of biomass with coal or natural gas with

CCS to make low net GHG-emitting transport fuels and or electricity.

Traditional biomass demand is steady or declines in most scenarios from 34 EJ yr^{-1}. The transport sector increases nearly tenfold from 2008 to 18–20 EJ yr^{-1} while modern uses for heat, power, combinations, and industry increase by factors of 2–4 from 18 EJ in 2008 (Fischedick *et al.*, 2011). The 2010 IEA model projects a contribution of 12 EJ yr^{-1} (11%) by 2035 to the transport sector, including 60% of advanced biofuels for road and aviation. Bioenergy supplies 5% of global power generation in 2035, up from 1% in 2008. Modern heat and industry doubles their contributions from 2008 (IEA, 2010c). The future potential deployment level varies at the global and national level depending on the technological developments, land availability, financial viability and mitigation policies.

Transformation pathway studies suggest that modern bioenergy could play a significant role within the energy system, providing 5–95 EJ yr^{-1} in 2030, 10–245 EJ yr^{-1} in 2050 and 105–325 EJ yr^{-1} in 2100 under full implementation scenarios, with immediate, global, and comprehensive incentives for land-related mitigation options. The scenarios project increasing deployment of bioenergy with tighter climate change targets, both in a given year as well as earlier in time. Models project increased dependence on, as well as increased deployment of, modern bioenergy, with some models projecting 35% of total primary energy from bioenergy in 2050, and as much as 50% of total primary energy from modern bioenergy in 2100. Bioenergy's share of regional total electricity and liquid fuels could be significant – up to 35% of global regional electricity from biopower by 2050, and up to 70% of global regional liquid fuels from biofuels by 2050. However, the cost-effective allocation of bioenergy within the energy system varies across models.

The high biomass deployment in scenarios from integrated assessment models is not uncontested. In particular, another class of sectoral studies, focusing on biophysical constraints, model assumptions (e.g., estimated increase in crop yields over large areas), and current observations, suggest to focus on the lower half of the ranges reported above (Campbell *et al.*, 2008; Field *et al.*, 2008; Haberl *et al.*, 2013c; Johnston *et al.*, 2009, 2011).

BECCS features prominently in many transformation scenarios. BECCS is deployed in greater quantities and earlier in time the more stringent the climate policy. Whether BECCS is essential for mitigation, or even sufficient, is unclear. The likelihood of BECCS deployment is difficult to evaluate and depends on safety confirmations, affordability and public acceptance (see section

Bioenergy technologies for details). BECCS may also affect the cost-effective emissions trajectory (Blanford *et al.*, 2013; Rose *et al.*, 2013).

Some integrated models are cost-effectively trading-off lower land carbon stocks and increased land N_2O emissions for the long-run mitigation benefits of bioenergy (A. Popp *et al.*, 2013; Rose *et al.*, 2013). These models suggest that in an optimal world bioenergy could contribute effectively to climate change mitigation despite land conversion and intensification emissions. In these models, constraining bioenergy has a cost. For instance, limiting global bioenergy availability to 100 EJ yr^{-1} tripled marginal abatement costs and doubled consumption losses associated with transformation pathways (Rose *et al.*, 2013).

Key point 8: Overall outcomes may depend strongly on governance of land use, increased yields, and deployment of best practices in agricultural, forestry and biomass production.

With increasing scarcity of productive land, the growing demand for food and bioenergy may incur substantial LUC causing high GHG emissions and/or increased agricultural intensification and higher N_2O emissions (Delucchi, 2010) unless wise integration of bioenergy into agriculture and forestry landscapes occurs. Integrated assessment models differ in their assumptions on availability of land resources for dedicated bioenergy crops. Either bioenergy crops will be allocated based on suitability of soil and climatic conditions and the competition with land needed for the production of other agricultural goods or bioenergy crops can only to be grown on land other than that required for food production. In general, avoiding deforestation restricts the availability for agricultural expansion. In some models nature conservation areas are not available for cropland expansion. Other models emphasize afforestation as an alternative to bioenergy as land-based carbon sequestration strategy. Different choices of bioenergy feedstocks (1st vs. 2nd generation but also woody vs. herbaceous cellulosic), land-use restrictions and current, as well as future management (such as irrigation vs. rainfed) for bioenergy production significantly affect simulated bioenergy crop yields. Agricultural yields in all models are assumed to change over time. Yield increases due to technological change are either considered mostly exogenously or treated endogenously. In some models food demand reacts to food prices and lower food demand is observed in mitigation scenarios. In other models, food demand is prescribed exogenously and therefore does react on higher food prices. As a result of ongoing population growth, rising per capita caloric intake and changing dietary preferences, such as an increased consumption of meat and dairy products, demand for

agricultural products in the future is anticipated to increase significantly (Popp *et al.*, 2013). Many models suggest relatively high deployment of bioenergy, as ambitious mitigation goals rely on making use of all available renewables. In particular, bioenergy is seen as more versatile, while solar and wind energy cannot as easily produce base load power or provide high-density fuels for transportation. If bioenergy, and especially BECCS, is not available, large-scale afforestation is seen as a necessary alternative land carbon sequestration strategy.

Consideration of LUC emissions in integrated assessment models show that valuing or protecting global terrestrial carbon stocks reduces the potential LUC-related GHG emissions of energy crop deployment, and could lower the cost of achieving climate change objectives, but could exacerbate increases in agricultural commodity prices (Popp *et al.*, 2011; Reilly *et al.*, 2012). It is important to note that integrated models are mostly investigating optimal realization pathways, assuming global prices on carbon (including the terrestrial land carbon stock); if such conditions cannot be realized, certain types of bioenergy could lead to additional GHG emissions. More generally, if the terrestrial land carbon stock remains unprotected, large GHG emissions from bioenergy related land-use change alone are possible (Calvin *et al.*, 2013; Creutzig *et al.*, 2012a; Melillo *et al.*, 2009; Wise *et al.*, 2009).

In summary, integrated model scenarios project between 10 and 245 EJ yr^{-1} modern bioenergy deployment in 2050. Good governance and favorable conditions for bioenergy development may result in higher deployment in bioenergy scenarios while sustainability and livelihood concerns might constrain the deployment of bioenergy scenarios to lower deployment values (see next section).

Bioenergy and sustainable development

The nature and extent of the impacts of deploying bioenergy depend on the specific system, the development context and on the size of the intervention. The effects on livelihoods have not yet been systematically evaluated in integrated assessments (Creutzig *et al.*, 2012b), even though human geography studies have shown that bioenergy deployment can have strong distributional impacts (Davis *et al.*, 2013; Muys *et al.*, 2014). The total effects on livelihoods will be mediated by global market dynamics, policy regulations and incentives, the production model and deployment scale, and place-specific factors such as labor and financial capabilities, governance, including land tenure security, among others (Creutzig *et al.*, 2013).

Bioenergy projects can be economically beneficial, e.g., by raising and diversifying farm incomes and

increasing rural employment through the production of biofuels for domestic (Gohin, 2008) or export (Arndt *et al.*, 2011b,c) markets (Wicke *et al.*, 2009).

Box 1

Some reported examples of cobenefits from biofuel production

Brazilian sugar cane ethanol production provides six times more jobs than the Brazilian petroleum sector and spreads income benefits across numerous municipalities (De Moraes *et al.*, 2010). Worker income is higher than in nearly all other agricultural sectors (De Moraes *et al.*, 2010; Satolo & Bacchi, 2013) and several sustainability standards have been adopted (Viana & Perez, 2013). Broader strategic planning, understanding of cumulative impacts, and credible and collaborative decision-making processes can help to enhance biodiversity and reverse ecological fragmentation, address direct and indirect land-use change, improve the quality and durability of livelihoods, and other sustainability issues (Duarte *et al.*, 2013).

Cobenefits of palm oil production have been reported in the major producer countries, Malaysia and Indonesia (Lam *et al.*, 2009; Sumathi *et al.*, 2008) as well as from new producer countries (Garcia-Ulloa *et al.*, 2012). Palm oil production results in employment creation as well as in increments of state and individual income (Lam *et al.*, 2009; Sayer *et al.*, 2012; Sumathi *et al.*, 2008; Tan *et al.*, 2009; Von Geibler, 2013). When combined with agroforestry palm oil plantations can increase food production locally and have a positive impact on biodiversity (Garcia-Ulloa *et al.*, 2012; Lam *et al.*, 2009) and when palm oil plantations are installed on degraded land further cobenefits on biodiversity and carbon enhancement may be realized (Garcia-Ulloa *et al.*, 2012; Sayer *et al.*, 2012; Sumathi *et al.*, 2008). Further, due to its high productivity palm oil plantations can produce the same bioenergy input using less land than other bioenergy crops (Sumathi *et al.*, 2008; Tan *et al.*, 2009). Certification in palm oil production can become a means for increasing sustainable production of biofuels (Tan *et al.*, 2009; Von Geibler, 2013).

Similarly, cobenefits from the production of Jatropha as a biofuel crop in developing countries have been reported, mainly when Jatropha is planted on degraded land. These include increases in individuals income (Arndt *et al.*, 2012; Garg *et al.*, 2011a,b), improvement in energy security at the local level (Muys *et al.*, 2014; Von Maltitz & Setzkorn, 2013), and reducing soil erosion (Garg *et al.*, 2011a,b).

The establishment of large-scale biofuels feedstock production, however, can also cause smallholders, tenants and herders to lose access to productive land, while other social groups such as workers, investors, company owners, biofuels consumers, and populations who are closer to for GHG emission reduction activities enjoy the benefits of this production (Van der Horst & Vermeylen, 2011). This is particularly relevant where large areas of land are still unregistered or are being claimed and under dispute by stakeholders (Dauvergne & Neville, 2010). In some cases increasing demand for first-generation bioenergy is partly driving the expansion of crops like soy and oil palm, which in turn contribute to promote large-scale agribusinesses at the expense of family and community-based agriculture (Wilkinson & Herrera, 2010). Biofuels deployment can also translate into reductions of time invested in on-farm subsistence and community-based activities, thus translating into lower productivity rates of subsistence crops and an increase in intracommunity conflicts as a result of the uneven share of collective responsibilities (Mingorría *et al.*, 2010, 2014).

Bioenergy deployment seems to be more beneficial when it is not an additional land-use activity expanding over the landscape, but rather integrates into existing land uses and influences the way farmers and forest owners use their land. Various studies indicate the ecosystem services and values that perennial crops have in restoring degraded lands, via agroforestry systems, controlling erosion and even in regional climate effects such as improved water retention and precipitation (Faaij, 2006; Van der Hilst *et al.*, 2012a; Wicke *et al.*, 2011b). Examples include adjustments in agriculture practices where farmers, for instance, change their manure treatment to produce biogas, reduce methane losses and reduce N losses. Changes in management practice may swing the net GHG balance of options and also have clear sustainable development implications (Davis *et al.*, 2012).

Small-scale bioenergy options can provide cost-effective alternatives for mitigating climate change, at the same time helping advance sustainable development priorities, particularly in rural areas of developing countries (see Box 1). The IEA (2011) estimates that 2.7 billion people worldwide depend on traditional biomass for cooking, while 84% of them belonged to rural communities. Use of low quality fuels and inefficient cooking and heating devices leads to pollution resulting in nearly 4 million premature deaths every year, and a range of chronic illnesses and other health problems (Lim *et al.*, 2012). Modern small-scale bioenergy systems reduce CO_2 emissions from unsustainable biomass harvesting and short-lived climate pollutants, e.g., black carbon, from cleaner combustion (Chung *et al.*, 2012;

FAO, 2010). As noted previously, scaling up clean cook-stove initiatives could not only save 2 million lives a year, but also significantly reduce GHG emissions. Efficient biomass cookstoves and biogas stoves at the same time provide multiple benefits: reduce pressure on forests and biodiversity, reduce exposure to smoke related health hazards, reduce drudgery for women in collecting fuelwood and save money if purchasing fuels (Martin *et al.*, 2011). Benefits from the dissemination of improved cookstoves outweigh their costs by 7-fold, when their health, economic, and environmental benefits are accounted for (Garcia-Frapolli *et al.*, 2010).

Table 1 presents a summary of potential impacts of bioenergy options on social, institutional, environmental, economic and technological conditions. The relationship between bioenergy and these conditions is complex and there could be negative or positive implications, depending on the type of bioenergy option, the scale of the production system and the local context, allowing intrinsic trade-offs (Edenhofer *et al.*, 2013). While biofuels can allow the reduction of fossil fuel use and of greenhouse gas emissions, they often shift environmental burdens toward land use-related impacts (i.e., eutrophication, acidification, water depletion, ecotoxicity) (EMPA, 2012; Smith & Torn, 2013; Tavoni & Socolow, 2013). Cobenefits and adverse side effects do not necessarily overlap, neither geographically nor socially (Dauvergne & Neville, 2010; Van der Horst & Vermeylen, 2011; Wilkinson & Herrera, 2010). The main potential cobenefits are related to access to energy and impacts on the economy and wellbeing, jobs creation and improvement of local resilience (Creutzig *et al.*, 2013; Walter *et al.*, 2011). Main risks of crop-based bioenergy for sustainable development and livelihoods include competition on arable land (Haberl *et al.*, 2013a) and consequential impact on food security, tenure arrangements, displacement of communities and economic activities, creation of a driver of deforestation, impacts on biodiversity, water and soil or increment in vulnerability to climate change, and unequal distribution of benefits (German *et al.*, 2011; Hall *et al.*, 2009; Sala *et al.*, 2000; SREX, 2012; Thompson *et al.*, 2011a,b).
Key point 9: The management of natural resources to provide needs for human society while recognizing environmental balance is the challenges facing society. Good governance is an essential component of a sustainable energy system.

Careful policies for implementation focused on land-use zoning approaches (including nature conservation and biodiversity protection), multifunctional land use, integration of food and energy production, avoidance of detrimental livelihood impacts e.g., on livestock grazing and subsistence farming, and consideration of equity

issues and sound management of impacts on water systems are crucial for sustainable solutions. Integrated studies that compare impacts of bioenergy production between different crops and land management strategies show that the overall impact (both ecological and socioeconomic) depends strongly on the governance of land use and design of the bioenergy system (see Van der Hilst *et al.*, 2012b in the European context and Van Dam *et al.*, 2009a,b for different crops and scenarios in Argentina). Van Eijck *et al.* (2012) show similar differences in impacts between the production and use of Jatropha based on smallholder production vs. plantation models. This implies that governance and planning have a strong impact on the ultimate result and impact of large-scale bioenergy deployment. Legislation and regulation of bioenergy as well as voluntary certification schemes are required to guide bioenergy production system deployment so that the resources and feedstocks be put to best use, and that (positive and negative) socio-economic and environmental issues are considered and addressed when needed (Batidzirai *et al.*, 2012; Baum *et al.*, 2012; Berndes *et al.*, 2008, 2004; Börjesson & Berndes, 2006; Busch, 2012; Dimitriou *et al.*, 2009, 2011; Dornburg *et al.*, 2010; Garg *et al.*, 2011a,b; Gopalakrishnan *et al.*, 2012, 2011a,b; Gopalakrishnan *et al.*, 2009; Parish *et al.*, 2012; Sparovek *et al.*, 2007). But the global potentials of such systems are difficult to determine (Berndes & Börjesson, 2007; Dale & Kline, 2013). Similarly, existing and emerging guiding principles and governance systems influence biomass resources availability (Stupak *et al.*, 2011). In this regard, certification approaches can be useful, but they should be accompanied by effective territorial policy frameworks (Hunsberger *et al.*, 2013). There are different options, from voluntary to legal and global agreements, to improve governance of biomass markets and land use that still require much further attention (Verdonk *et al.*, 2007).

Trade-offs and synergies with land, water, food and biodiversity

This section summarizes results from integrated models (models that have a global aggregate view, but cannot disaggregate place-specific effects in biodiversity and livelihoods discussed above) on land, water, food and biodiversity. In these models, at any level of future bioenergy supply, land demand for bioenergy depends on (i) the share of bioenergy derived from wastes and residues (Rogner *et al.*, 2012); (ii) the extent to which bioenergy production can be integrated with food or fiber production, which ideally results in synergies (Garg *et al.*, 2011a,b; Sochacki *et al.*, 2012) or at least mitigates land-use competition (Berndes *et al.*, 2013); (iii) the

Table 1 Potential institutional, social, environmental, economic, and technological implications of bioenergy options at local to global scale

	Scale	
Institutional issues and Governance systems		
May contribute to energy independence (+), especially at the local level (reduce dependency on fossil fuels) (2, 20, 32, 39, 50)	+	Local to national
Can improve (+) or decrease (−) land tenure and use rights for local stakeholders (2, 17, 38, 50)	+/−	Local
Cross-sectoral coordination (+) or conflicts (−) between forestry, agriculture, energy and/or mining (2, 13, 26, 31, 59)	+/−	Local to national
Impacts on labor rights among the value chain (2, 6, 17)	+/−	Local to national
Promoting of participative mechanisms for small-scale producers (14, 15)	+	Local to national
Social		
Competition with food security including food availability (through reduced food production at the local level), food access (due to price volatility) use usage (as food crops can be diverted toward biofuel production) and consequently to food stability. Bioenergy derived from residues, wastes or by-products is an exception (1,2, 7, 9, 12, 18, 23)	−	Local to global
Integrated systems (including agroforestry) can improve food production at the local level creating a positive impact toward food security (51, 52, 53, 66, 70, 71, 72). Further, biomass production combined with improved agricultural management can avoid such competition and bring investment in agricultural production systems with overall improvements of management as a result (as observed in Brazil) (59, 62, 67, 68)	+	Local
Increasing (+) or decreasing (−) existing conflicts or social tension (9, 14, 19, 26)	+/−	Local to national
Impacts on traditional practices: using local knowledge in production and treatment of bioenergy crops (+) or discouraging local knowledge and practices (−) (2, 50)	+/−	Local
Displacement of small-scale farmers (14, 15, 19). Bioenergy alternatives can also empower local farmers by creating local income opportunities	+/−	Local
Promote capacity building and new skills (3, 15, 50)	+	Local
Gender impacts (2, 4, 14, 15, 27)	+/−	Local to national
Efficient biomass techniques for cooking (e.g., biomass cookstoves) can have positive impacts on health specially for women and children in developing countries (42, 43, 44)	+	Local to national
Environmental		
Biofuel plantations can promote deforestation and/or forest degradation, under weak or no regulation (1, 8, 22)	−	Local to global
When used on degraded lands, perennial crops offer large-scale potential to improve soil carbon and structure, abate erosion and salinity problems. Agroforestry schemes can have multiple benefits including increased overall biomass production, increase biodiversity and higher resilience to climate changes (58, 63, 64, 66, 71)	+	Local to global
Some large-scale bioenergy crops can have negative impacts on soil quality, water pollution and biodiversity. Similarly potential adverse side effects can be a consequence of increments in use of fertilizers for increasing productivity (7, 12, 26, 30). Experience with sugarcane plantations has shown that they can maintain soil structure (56) and application of pesticides can be substituted by the use of natural predators and parasitoids (68)	−/+	Local to transboundary
Can displace activities or other land uses (8, 26)	−	Local to global
Smart modernization and intensification can lead to lower environmental impacts and more efficient land use (73, 74)	+	Local to transboundary
Creating bioenergy plantations on degraded land can have positive impacts on soil and biodiversity (12)	+	Local to transboundary
There can be trade-offs between different land uses, reducing land availability for local stakeholders (45, 46, 47, 48, 49). Multicropping system provide bioenergy while better maintaining ecological diversity and reducing land use competition (57)	−/+	Local to national
Ethanol utilization leads to the phase-out of lead additives and MBTE and reduces sulfur, particulate matter and carbon monoxide emissions (55)	+	Local to global
Economic		
Increase in economic activity, income generation and income diversification (1, 2, 3, 12, 20, 21, 27, 54)	+	Local
Increase (+) or decrease (−) market opportunities (16, 27, 31)	+/−	Local to national
Contribute to the changes in prices of feedstock (2, 3, 5, 21)	+/−	Local to global

Table 1 (continued)

		Scale
May promote concentration of income and/or increase poverty if sustainability criteria and strong governance is not in place (2, 16, 26)	−	Local to regional
Using waste and residues may create socio-economic benefits with little environmental risks (2, 41, 36)	+	Local to regional
Uncertainty about mid- and long term revenues (6, 30)	−	National
Employment creation (3, 14, 15)	+	Local to regional
Technological		
Can promote technology development and/or facilitate technology transfer (2, 27, 31)	+	Local to global
Increasing infrastructure coverage (+). However if access to infrastructure and/or technology is reduced to few social groups it can increase marginalization (−) (27, 28, 29)	+/−	Local
Bioenergy options for generating local power or to use residues may increase labor demand, creating new job opportunities. Participatory technology development also increases acceptance and appropriation (6, 8, 10, 37, 40)	+	Local
Technology might reduce labor demand (−). High dependent of tech. transfer and/or acceptance	−	Local

(1) (Finco & Doppler, 2010); (2) (Amigun *et al.*, 2011); (3) (Arndt *et al.*, 2012); (4) (Arndt *et al.*, 2011a); (5) (Arndt *et al.*, 2011a,b); (6) (Awudu & Zhang, 2012); (7) (Beringer *et al.*, 2011); (8) (Borzoni, 2011); (9) (Bringezu *et al.*, 2012); (10) (Cacciatore *et al.*, 2012); (11) (Cançado *et al.*, 2006); (12) (Danielsen *et al.*, 2009);(13) (Diaz-Chavez, 2011); (14) (Duvenage *et al.*, 2013); (15) (Ewing & Msangi, 2009); (16) (Gasparatos *et al.*, 2011); (17) (German & Schoneveld, 2012); (18) (Haberl *et al.*, 2011); (19) (Hall *et al.*, 2009); (20) (Hanff *et al.*, 2011); (21) (Huang *et al.*, 2012); (22) (Koh & Wilcove, 2008); (23) (Koizumi, 2013); (24) (Kyu *et al.*, 2010); (25) (Madlener *et al.*, 2006); (26) (Martinelli & Filoso, 2008); (27) (Mwakaje, 2012); (28) (Oberling *et al.*, 2012); (29) (Schut *et al.*, 2010); (30) (Selfa *et al.*, 2011); (31) (Steenblik, 2007); (32) (Stromberg & Gasparatos, 2012); (33) (Searchinger *et al.*, 2009); (34) (Searchinger *et al.*, 2008); (35) (Smith & Searchinger, 2012); (36) (Tilman *et al.*, 2009); (37) (Van de Velde *et al.*, 2009); (38) (Von Maltitz & Setzkorn, 2013); (39) (Wu & Lin, 2009); (40) (Zhang *et al.*, 2011); (41) (Fargione *et al.*, 2008); (42) (Jerneck & Olsson, 2013); (43) (Gurung & Oh, 2013); (44) (O'Shaughnessy *et al.*, 2013); (45) (German *et al.*, 2013); (46) (Cotula, 2012); (47) (Mwakaje, 2012); (48) (Scheidel & Sorman, 2012); (49) (Haberl *et al.*, 2013b); (50) (Muys *et al.*, 2014); (51) (Egeskog *et al.*, 2011); (52) (Diaz-Chavez, 2012); (53) (Ewing & Msangi, 2009); (54) (De Moraes *et al.*, 2010); (55) (Goldemberg, 2007); (56) (Walter *et al.*, 2008); (57) (Langeveld *et al.*, 2013); (58) (Van Dam *et al.*, 2009a,b); (59) (Van Dam *et al.*, 2010); (60) (Van Eijck *et al.*, 2012); (61) (van Eijck *et al.*, 2013, 2014); (62) (Martínez *et al.*, 2013); (63) (Van der Hilst *et al.*, 2010); (64) (Van der Hilst *et al.*, 2012a,b,c); (65) (Hoefnagels *et al.*, 2013); (66) (Immerzeel *et al.*, 2014); (67) (Lynd *et al.*, 2011); (68) (Smeets *et al.*, 2008); (69) (Smeets & Faaij, 2010); (70) (Wicke *et al.*, 2011a); (71) (Wicke *et al.*, 2013); (72) (Wiskerke *et al.*, 2010); (73) (De Wit *et al.*, 2011); (74) (De Wit *et al.*, 2013).

extent to which bioenergy can be grown on areas with little current or future production, taking into account growing land demand for food (Nijsen *et al.*, 2012); and (iv) the volume of dedicated energy crops and their yields (Batidzirai *et al.*, 2012; Haberl *et al.*, 2010; Smith *et al.*, 2012a). Energy crop yields per unit area may differ by factors of >10 depending on differences in natural fertility (soils, climate), energy crop plants, previous land use, management and technology (Beringer *et al.*, 2011; Erb, 2012; Johnston *et al.*, 2009; Lal, 2010; Pacca & Moreira, 2011; Smith *et al.*, 2012a). Assumptions on energy crop yields are one of the main reasons for the large differences in estimates of future area demand of energy crops (Popp *et al.*, 2013). Likewise, assumptions on yields, strategies and governance on future food/feed crops have large implications for assessments of the degree of land competition between biofuels and these land uses (Batidzirai *et al.*, 2012; De Wit *et al.*, 2013).

However, across models, there are very different potential landscape transformation visions in all regions.

Overall, it is difficult to generalize on regional land cover effects of mitigation. Some models assume significant land conversion while other models do not. In idealized implementation scenarios, there is expansion of energy cropland and forest land in many regions, with some models exhibiting very strong forest land expansion and others very little by 2030. Land conversion is increased in the 450 ppm scenarios compared to the 550 ppm scenarios, but at a declining share, a result consistent with a declining land-related mitigation rate with policy stringency. The results of these integrated model studies need to be interpreted with caution, as not all GHG emissions and biogeophysical or socio-economic effects of bioenergy deployment are incorporated into these models, and as not all relevant technologies are represented (e.g., cascade utilization).

Large-scale bioenergy production from dedicated crops may affect water availability and quality, which are highly dependent on (i) type and quantity of local freshwater resources; (ii) necessary water quality; (iii) competition for multiple uses (agricultural, urban,

industrial, power generation); and (iv) efficiency in all sector end-uses (Coelho *et al.*, 2012; Gerbens-Leenes *et al.*, 2009). In many regions, additional irrigation of energy crops could further intensify existing pressures on water resources (Popp *et al.*, 2011). Studies indicate that an exclusion of severe water scarce areas for bioenergy production (mainly to be found in the Middle East, parts of Asia and western USA) would reduce global technical bioenergy potentials by 17% until 2050 (Van Vuuren *et al.*, 2009). A model comparison study with five global economic models shows that the aggregate food price effect of large-scale lignocellulosic bioenergy deployment (i.e. 100 EJ globally by the year 2050) is significantly lower (+5% on average across models) than the potential price effects induced by climate impacts on crop yields [+25% on average across models (Lotze-Campen *et al.*, 2013)]. Hence, ambitious climate change mitigation need not drive up global food prices much, if the extra land required for bioenergy production is accessible or if the feedstock, e.g., from forests, does not directly compete for agricultural land. Effective land-use planning and strict adherence to sustainability criteria need to be integrated to large-scale bioenergy projects to minimize competitions for water (for example, by excluding the establishment of biofuel projects in irrigated areas). If bioenergy is not managed properly, additional land demand and associated land use change may put pressures on biodiversity (Groom *et al.*, 2008; Reilly *et al.*, 2012; Popp *et al.*, 2011; Wise *et al.*, 2009). However, implementing appropriate management, such as establishing bioenergy crops in degraded areas represents an opportunity where bioenergy can be used to achieve positive environmental outcomes (Nijsen *et al.*, 2012; Immerzeel *et al.*, 2014).

Conclusion

The climate change mitigation value of bioenergy systems depends on several factors, some of which are challenging to quantify. We estimate the sustainable technical potential as up to 100 EJ: high agreement; 100–300 EJ: medium agreement; above 300 EJ: low agreement. Stabilization scenarios indicate that bioenergy may supply from 10 to 245 EJ yr^{-1} to global primary energy supply by 2050. Large-scale deployment (>200 EJ) could realize high GHG emissions savings if technological and governance preconditions are met, but such high deployment of land-intensive bioenergy feedstocks could also lead to detrimental climate effects, negatively impact ecosystems, biodiversity and livelihoods otherwise. Cellulosic feedstocks, increased end-use efficiency, improved land carbon-stock management and residue use, and, when fully developed, carbon dioxide capture and storage from bioenergy appear as the most promising options, depending on development costs, implementation, learning, and risk management. The deployment of small-scale bioenergy systems such as biogas and efficient wood stoves for cooking, small-scale decentralized biomass combustion and gasification for rural electrification could not only reduce GHG emissions but also promote other dimensions of sustainable development.

One strand of literature highlights that bioenergy could contribute significantly to mitigating global GHG emissions via displacing fossil fuels, better management of natural resources, and possibly by deploying BECCS. Another strand of literature points to abundant risks in the large-scale development of bioenergy mainly from dedicated energy crops and particularly in reducing the land carbon stock, potentially resulting in net increases in GHG emissions.

The climate impacts of bioenergy systems are site and case specific, given the large dependence on local factors (especially for biogeophysical and biogeochemical aspects). For any bioenergy system to deliver net climate benefits with few negative environmental or socio-economic impacts, will require attention to a range of factors that influence land-use change related GHG emissions and biogeophysical perturbations; displacement of other land and water uses; other livelihood aspects such as employment, land access and social assets; and biodiversity. Other crucial factors influencing mitigation potential are biomass feedstock and production practices, the conversion technologies used, whether BECCS can be deployed economically and safely, and the magnitude of market-mediated effects such as ILUC and fossil fuel displacement. The estimated mitigation potential also depends on exactly how the accounting is performed (e.g., definition of baseline conditions and system boundaries).

We conclude that the high variability in pathways, uncertainties in technological development and ambiguity in political decision-making render forecasts on deployment levels and climate effects very difficult. Thus there is need for research and development to address many of these uncertainties. However, uncertainty about projections should not preclude pursuing clearly beneficial bioenergy options.

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References

Amigun B, Musango JK, Stafford W (2011) Biofuels and sustainability in Africa. *Renewable and Sustainable Energy Reviews*, **15**, 1360–1372.

Anderson R, Canadell J, Randerson J, Jackson R, Hungate B, Baldocchi D, O'Halloran T (2011) Biophysical considerations in forestry for climate protection. *Frontiers in Ecology and the Environment*, **9**, 174–182.

Anderson-Teixeira K, Snyder P, Twine T, Cuadra S, Costa M, DeLucia E (2012) Climate-regulation services of natural and agricultural ecoregions of the Americas. *Nature Climate Change*, **2**, 177–181.

Anenberg S, Balakrishnan K, Jetter J, Masera O, Mehta S, Moss J, Ramanathan V (2013) Cleaner cooking solutions to achieve health, climate, and economic cobenefits. *Environmental Science & Technology*, **47**, 3944–3952.

Argo A, Tan E, Inman D, Langholtz M, Eaton L, Jacobson J, Graham R (2013) Investigation of biochemical biorefinery sizing and environmental sustainability impacts for conventional bale system and advanced uniform biomass logistics designs. *Biofuels, Bioproducts and Biorefining*, **7**, 282–302.

Arndt C, Benfica R, Thurlow J (2011a) Gender implications of biofuels expansion in Africa: the case of Mozambique. *World Development*, **39**, 1649–1662.

Arndt C, Msangi S, Thurlow J (2011b) Are biofuels good for African development? An analytical framework with evidence from Mozambique and Tanzania. *Biofuels*, **2**, 221–234.

Arndt C, Robinson S, Willenbockel D (2011c) Ethiopia's growth prospects in a changing climate: a stochastic general equilibrium approach. *Global Environmental Change*, **21**, 701–710.

Arndt C, Pauw K, Thurlow J (2012) Biofuels and economic development: a computable general equilibrium analysis for Tanzania. *Energy Economics*, **34**, 1922–1930.

Arora V, Montenegro A (2011) Small temperature benefits provided by realistic afforestation efforts. *Nature Geoscience*, **4**, 514–518.

Awudu I, Zhang J (2012) Uncertainties and sustainability concepts in biofuel supply chain management: a review. *Renewable and Sustainable Energy Reviews*, **16**, 1359–1368.

Bacovsky D, Dallos M, Achard M (2010) Status of 2 nd Generation Biofuels Demonstration Facilities in June 2010: A Report to IEA Bioenergy Task 39 (No. T39-P1b, 27). Available at: http://www.ascension-publishing.com/BIZ/IEATask39-0610.pdf (accessed April 2014).

Bala G, Caldeira K, Wickett M, Phillips T, Lobell D, Delire C, Mirin A (2007) Combined climate and carbon-cycle effects of large-scale deforestation. *Proceedings of the National Academy of Sciences*, **104**, 6550–6555.

Baliban R, Elia J, Floudas C (2013) Biomass and natural gas to liquid transportation fuels: process synthesis, global optimization, and topology analysis. *Industrial & Engineering Chemistry Research*, **52**, 3381–3406.

Bathiany S, Claussen M, Brovkin V, Raddatz T, Gayler V (2010) Combined biogeophysical and biogeochemical effects of large-scale forest cover changes in the MPI earth system model. *Biogeosciences*, **7**, 1383–1399.

Batidzirai B, Smeets E, Faaij A (2012) Harmonising bioenergy resource potentials - methodological lessons from review of state of the art bioenergy potential assessments. *Renewable and Sustainable Energy Reviews*, **16**, 6598–6630.

Baum S, Bolte A, Weih M (2012) Short rotation coppice (SRC) plantations provide additional habitats for vascular plant species in agricultural mosaic landscapes. *Bioenergy Research*, **5**, 573–583.

Beringer T, Lucht W, Schaphoff S (2011) Bioenergy production potential of global biomass plantations under environmental and agricultural constraints. *GCB Bioenergy*, **3**, 299–312.

Berndes G, Börjesson P (2007) Multifunctional bioenergy systems. The AGS Pathways Report 2007: EU1. AGS - Alliance for Global Sustainability: Swiss Federal Institute of Technology, Massachusetts Institute of Technology, Chalmers University of Technology, Tokyo University.

Berndes G, Fredriksson F, Börjesson P (2004) Cadmium accumulation and Salix based phytoextraction on arable land in Sweden. *Agriculture, Ecosystems & Environment*, **103**, 207–223.

Berndes G, Börjesson P, Ostwald M, Palm M (2008) Multifunctional biomass production systems - an introduction with presentation of specific applications in India and Sweden. *Biofuels, Bioproducts and Biorefining*, **2**, 16–25.

Berndes G, Bird N, Cowie A (2011) Bioenergy, Land Use Change and Climate Change Mitigation. Technical Report. International Energy Agency. Available at: http://www.ieabioenergy.com/wp-content/uploads/2013/10/Bioenergy-Land-Use-Change-and-Climate-Change-Mitigation-Background-Technical-Report.pdf (accessed April 2014).

Berndes G, Ahlgren S, Börjesson P, Cowie A (2013). Bioenergy and land use change-state of the art. *Wiley Interdisciplinary Reviews: Energy and Environment*, **2**, 282–303.

Bernier P, Paré D (2013) Using ecosystem CO2 measurements to estimate the timing and magnitude of greenhouse gas mitigation potential of forest bioenergy. *GCB Bioenergy*, **5**, 67–72.

Betts R (2001) Biogeophysical impacts of land use on present-day climate: near-surface temperature change and radiative forcing. *Atmospheric Science Letters*, **2**, 39–51.

Betts R (2007) Implications of land ecosystem-atmosphere interactions for strategies for climate change adaptation and mitigation. *Tellus B*, **59**, 602–615.

Betts R (2011) Mitigation: a sweetener for biofuels. *Nature Climate Change*, **1**, 99–101.

Blanford G, Merrick J, Richels R, Rose S (2013) Trade-offs Between mitigation costs and temperature change. *Climatic Change*, **123**, 527–541.

Bonan G (2008) Forests and climate change: forcings, feedbacks, and the climate benefits of forests. *Science*, **320**, 1444–1449.

Börjesson P, Berndes G (2006) The prospects for willow plantations for wastewater treatment in Sweden. *Biomass and Bioenergy*, **30**, 428–438.

Borzoni M (2011) Multi-scale integrated assessment of soybean biodiesel in Brazil. *Ecological Economics*, **70**, 2028–2038.

Brandão M, Milà i Canals L, Clift R (2011) Soil organic carbon changes in the cultivation of energy crops: implications for GHG balances and soil quality for use in LCA. *Biomass and Bioenergy*, **35**, 2323–2336.

Bridgwater A (2012) Upgrading biomass fast pyrolysis liquids. *Environmental Progress & Sustainable Energy*, **31**, 261–268.

Bright R, Strømman A, Peters G (2011) Radiative forcing impacts of boreal forest biofuels: a scenario study for Norway in light of albedo. *Environmental Science & Technology*, **45**, 7570–7580.

Bringezu S, O'Brien M, Schütz H (2012) Beyond biofuels: assessing global land use for domestic consumption of biomass: a conceptual and empirical contribution to sustainable management of global resources. *Land Use Policy*, **29**, 224–232.

Busch G (2012) GIS-based tools for regional assessments and planning processes regarding potential environmental effects of poplar SRC. *Bioenergy Research*, **5**, 584–605.

Cacciatore MA, Scheufele DA, Shaw BR (2012) Labeling renewable energies: how the language surrounding biofuels can influence its public acceptance. *Energy Policy*, **51**, 673–682.

Cai Z, Laughlin R, Stevens R (2001) Nitrous oxide and dinitrogen emissions from soil under different water regimes and straw amendment. *Chemosphere*, **42**, 113–121.

Calvin K, Wise M, Luckow P, Kyle P, Clarke L, Edmonds J (2013) Implications of uncertain future fossil energy resources on bioenergy use and terrestrial carbon emissions. *Climatic Change*, 1–12. doi: 10.1007/s10584-013-0923-0.

Campbell J, Lobell D, Genova R, Field C (2008) The global potential of bioenergy on abandoned agriculture lands. *Environmental Science & Technology*, **42**, 5791–5794.

Campbell J, Lobell D, Field C (2009) Greater transportation energy and GHG Offsets from bioelectricity than ethanol. *Science*, **324**, 1055–1057.

Canadell J, Raupach M (2008) Managing forests for climate change mitigation. *Science*, **320**, 1456–1457.

Cançado JED, Saldiva PHN, Pereira LAA, Lara LBLS, Artaxo P, Martinelli LA, Braga ALF (2006) The impact of sugar cane-burning emissions on the respiratory system of children and the elderly. *Environmental Health Perspectives*, **114**, 725–729.

Cao L, Caldeira K (2010) Atmospheric carbon dioxide removal: long-term consequences and commitment. *Environmental Research Letters*, **5**, 024011.

Carpita N (2012) Progress in the biological synthesis of the plant cell wall: new ideas for improving biomass for bioenergy. *Current Opinion in Biotechnology*, **23**, 330–337.

Chen X, Khanna M (2012) The market-mediated effects of low carbon fuel policies. *AgBioForum*, **15**, 1–17.

Cherubini F, Bright R, Strømman A (2012) Site-specific global warming potentials of biogenic CO2 for bioenergy: contributions from carbon fluxes and albedo dynamics. *Environmental Research Letters*, **7**, 045902.

Cherubini F, Bright R, Strømman A (2013) Global climate impacts of forest bioenergy: what, when and how to measure? *Environmental Research Letters*, **8**, 014049.

Cherubini F, Peters GP, Berntsen T, Strømman AH, Hertwich E (2011) CO2 emissions from biomass combustion for bioenergy: atmospheric decay and contribution to global warming. *GCB Bioenergy*, **3**, 413–426.

Chum H, Faaij A, Moreira J, Berndes G, Dhamija P, Dong H, Pingoud K (2011). Bioenergy. In *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*, (eds Edenhofer O, Pichs-Madruga R, Sokona Y, Seyboth K, Matschoss P, Kadner S, Zwickel T, Eickemeier P, Hansen G, Schlömer S, Von Stechow C), pp. 209–332. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Chung C, Ramanathan V, Decremer D (2012) Observationally constrained estimates of carbonaceous aerosol radiative forcing. *Proceedings of the National Academy of Sciences*, **109**, 11624–11629.

Ciais P, Schelhaas MJ, Zaehle S, Piao SL, Cescatti A, Liski J, Bouriaud O (2008) Carbon accumulation in European forests. *Nature Geoscience*, **1**, 425–429.

Clair S, Hillier J, Smith P (2008) Estimating the pre-harvest greenhouse gas costs of energy crop production. *Biomass and Bioenergy*, **32**, 442–452.

Claussen M, Brovkin V, Ganopolski A (2001) Biogeophysical versus biogeochemical feedbacks of large-scale land cover change. *Geophysical Research Letters*, **28**, 1011–1014.

Coelho S, Agbenyega O, Agostini A, Erb K, Haberl H, Hoogwijk M, Moreira J (2012). Chapter 20 - land and water: linkages to bioenergy. In *Global Energy Assessment - Toward a Sustainable Future* (eds Johansson TB, Nakicenovic N, Patwardhan A, Gomez-Echeverri L), pp. 1459–1526. Cambridge University Press, International Institute for Applied Systems Analysis, Laxenburg, Austria, Cambridge, UK and New York, NY, USA. Available at: www.globalenergyassessment.org (accessed April 2014).

Cordes L (2011). Igniting change: a strategy for universal adoption of clean cookstoves and fuels. *Global Alliance for Clean Cookstoves (GACC)*.

Cotula L (2012) The international political economy of the global land rush: a critical appraisal of trends, scale, geography and drivers. *Journal of Peasant Studies*, **39**, 649–680.

Creutzig F, Kammen DM (2010). Getting the carbon out of transportation fuels. In: *Global Sustainability - A Nobel Cause* (eds Schellnhuber HJ, Molina M, Stern N, Huber V, Kadner S), pp. 307–318. Cambridge University Press, UK. Available at: http://www.mcc-berlin.net/~creutzig/nobel.pdf (accessed April 2014).

Creutzig F, Popp A, Plevin R, Luderer G, Minx J, Edenhofer O (2012a) Reconciling top-down and bottom-up modeling on future bioenergy deployment. *Nature Climate Change*, **2**, 320–327.

Creutzig F, Stechow C, Klein D, Hunsberger C, Bauer N, Popp A, Edenhofer O (2012b) Can bioenergy assessments deliver? *Economics of Energy & Environmental Policy*, **1**, 65–82.

Creutzig F, Corbera E, Bolwig S, Hunsberger C (2013) Integrating place-specific livelihood and equity outcomes into global assessments of bioenergy deployment. *Environmental Research Letters*, **8**, 035047.

Daigneault A, Sohngen B, Sedjo R (2012) Economic approach to assess the forest carbon implications of biomass energy. *Environmental Science & Technology*, **46**, 5664–5671.

Dale V, Kline K (2013) Issues in using landscape indicators to assess land changes. *Ecological Indicators*, **28**, 91–99.

Dale V, Kline K, Perla D, Lucier A (2013) Communicating about bioenergy sustainability. *Environmental Management*, **51**, 279–290.

Danielsen F, Beukema H, Burgess ND, Parish F, Brühl CA, Donald PF, Fitzherbert EB (2009) Biofuel plantations on forested lands: double jeopardy for biodiversity and climate. *Conservation Biology*, **23**, 348–358.

Dauber J, Brown C, Fernando AL, Finnan J, Krasuska E, Ponitka J, Weih M (2012) Bioenergy from 'surplus' land: environmental and socio-economic implications, *BioRisk: Biodiversity & Ecosystem Risk Assessment*, **7**, 5–50.

Dauvergne P, Neville K (2010) Forests, food, and fuel in the tropics: the uneven social and ecological consequences of the emerging political economy of biofuels. *Journal of Peasant Studies*, **37**, 631–660.

Davin E, de Noblet-Ducoudré N, Friedlingstein P (2007) Impact of land cover change on surface climate: relevance of the radiative forcing concept. *Geophysical Research Letters*, **34**, L13702.

Davis R, Aden A, Pienkos P (2011) Techno-economic analysis of autotrophic microalgae for fuel production. *Applied Energy*, **88**, 3524–3531.

Davis S, Parton W, Grosso S, Keough C, Marx E, Adler P, DeLucia E (2012) Impact of second-generation biofuel agriculture on greenhouse-gas emissions in the corn-growing regions of the US. *Frontiers in Ecology and the Environment*, **10**, 69–74.

Davis S, Boddey R, Alves B, Cowie A, George B, Ogle S, Van Wijk M (2013) Management swing potential for bioenergy crops. *GCB Bioenergy*, **5**, 623–638.

De Moraes M, Da Costa C, Guilhoto J, De Souza L, De Oliveira F (2010) Social Externalities of Fuels. In: *Ethanol and Bioelectricity: Sugarcane in the Future of the Energy Matrix* (eds. Leão de Sousa EL, Isaias de Carvalho Macedo), pp. 44–75.

De Wit M, Londo M, Faaij A (2011) Productivity developments in European agriculture: relations to and opportunities for biomass production. *Renewable and Sustainable Energy Reviews*, **15**, 2397–2412.

De Wit M, Junginger M, Faaij A (2013) Learning in dedicated wood production systems: past trends, future outlook and implications for bioenergy. *Renewable and Sustainable Energy Reviews*, **19**, 417–432.

DeCicco J (2013) Biofuel's carbon balance: doubts, certainties and implications. *Climatic Change*, **121**, 801–814.

Delucchi M (2010) Impacts of biofuels on climate change, water use, and land use. *Annals of the New York Academy of Sciences*, **1195**, 28–45.

Diaz-Chavez RA (2011) Assessing biofuels: aiming for sustainable development or complying with the market? *Energy Policy*, **39**, 5763–5769.

Diaz-Chavez RA (2012) Land use for integrated systems: a bioenergy perspective. *Environmental Development*, **3**, 91–99.

Dimitriou I, Baum C, Baum S, Busch G, Schulz U, Köhn J, Bolte A (2009) Short rotation coppice (SRC) cultivation and local impact on the environment. *Landbauforschung vTI Agriculture and Forestry Research*, **3**, 159–162.

Dimitriou I, Baum C, Baum S, Busch G, Schulz U, Köhn J, Bolte A (2011). Quantifying environmental effects of short rotation coppice (SRC) on biodiversity, soil and water. *IEA Bioenergy Task*, **43**.

DiPietro P, Balash P, Wallace M (2012). A note on sources of CO_2 supply for enhanced-oil-recovery operations. *SPE Economics & Management*, **12**, 1652–1654.

Don A, Osborne B, Hastings A, Skiba U, Carter M, Drewer J, Zenone T (2012) Land-use change to bioenergy production in Europe: implications for the greenhouse gas balance and soil carbon. *GCB Bioenergy*, **4**, 372–391.

Dornburg V, Van Vuuren D, Van de Ven G, Langeveld H, Meeusen M, Banse M, Faaij A (2010) Bioenergy revisited: key factors in global potentials of bioenergy. *Energy and Environmental Science*, **3**, 258–267.

Drabik D, De Gorter H (2011) Biofuel policies and carbon leakage. *AgBioForum*, **14**, 104–110.

Duarte C, Gaudreau K, Gibson R, Malheiros T (2013) Sustainability assessment of sugarcane-ethanol production in Brazil: a case study of a sugarcane mill in São Paulo state. *Ecological Indicators*, **30**, 119–129.

Dumortier J, Hayes D, Carriquiry M, Dong F, Du X, Elobeid A, Tokgoz S (2011) Sensitivity of carbon emission estimates from indirect land-use change. *Applied Economic Perspectives and Policy*, **33**, 428–448.

Duvenage I, Langston C, Stringer LC, Dunstan K (2013) Grappling with biofuels in Zimbabwe: depriving or sustaining societal and environmental integrity? *Journal of Cleaner Production*, **42**, 132–140.

Edenhofer O, Seyboth K, Creutzig F, Schlömer S (2013) On the sustainability of renewable energy sources. *Annual Review of Environment and Resources*, **38**, 169–200.

Egeskog A, Berndes G, Freitas F, Gustafsson S, Sparovek G (2011) Integrating bioenergy and food production—A case study of combined ethanol and dairy production in Pontal, Brazil. *Energy for Sustainable Development*, **15**, 8–16.

van Eijck J, Romijn H, Smeets E *et al.* (2013) Comparative analysis of key socio-economic and environmental impacts of smallholder and plantation based jatropha biofuel production systems in Tanzania. *Biomass and Bioenergy*, **61**, 24–45.

van Eijck J, Romijn H, Balkema A, Faaij A (2014) Global experience with jatropha cultivation for bioenergy: an assessment of socio-economic and environmental aspects. *Renewable and Sustainable Energy Reviews*, **32**, 869–889.

Eisenbies M, Vance E, Aust W, Seiler J (2009) Intensive utilization of harvest residues in southern pine plantations: quantities available and implications for nutrient budgets and sustainable site productivity. *BioEnergy Research*, **2**, 90–98.

Elliott D (2013) Transportation fuels from biomass via fast pyrolysis and hydroprocessing. *Wiley Interdisciplinary Reviews: Energy and Environment*, **2**, 525–533.

EMPA (2012). Harmonisation and Extension of the Bioenergy Inventories and Assessment: End Report.

Eranki P, Dale B (2011) Comparative life cycle assessment of centralized and distributed biomass processing systems combined with mixed feedstock landscapes. *GCB Bioenergy*, **3**, 427–438.

Erb K (2012) How a socio-ecological metabolism approach can help to advance our understanding of changes in land-use intensity. *Ecological Economics*, **76**, 8–14.

Erb K, Gaube V, Krausmann F, Plutzar C, Bondeau A, Haberl H (2007) A comprehensive global 5 min resolution land-use data set for the year 2000 consistent with national census data. *Journal of Land Use Science*, **2**, 191–224.

Erb K, Haberl H, Plutzar C (2012) Dependency of global primary bioenergy crop potentials in 2050 on food systems, yields, biodiversity conservation and political stability. *Energy Policy*, **47**, 260–269.

Erb K-H, Kastner T, Luyssaert S, Houghton RA, Kuemmerle T, Olofsson P, Haberl H (2013) Bias in the attribution of forest carbon sinks. *Nature Climate Change*, **3**, 854–856.

Ewing M, Msangi S (2009) Biofuels production in developing countries: assessing tradeoffs in welfare and food security. *Environmental Science & Policy*, **12**, 520–528.

Faaij A (2006) Modern biomass conversion technologies. *Mitigation and Adaptation Strategies for Global Change*, **11**, 335–367.

FAO (2010). What Wood Fuels can do to Mitigate Climate Change (FAO forestry paper No. 162).

Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P (2008) Land clearing and the biofuel carbon debt. *Science*, **319**, 1235–1238.

Favaro L, Jooste T, Basaglia M, Rose S, Saayman M, Görgens J, Van Zyl W (2013) Designing industrial yeasts for the consolidated bioprocessing of starchy biomass to ethanol. *Bioengineered*, **4**, 0–1.

Field C, Campbell J, Lobell D (2008) Biomass energy: the scale of the potential resource. *Trends in Ecology and Evolution*, **23**, 65–72.

Finco MVA, Doppler W (2010) Bioenergy and sustainable development: the dilemma of food security in the Brazilian savannah. *Energy for Sustainable Development*, **14**, 194–199.

Finkbeiner M (2013) *Indirect Land Use Change (iLUC) within Life Cycle Assessment (LCA) – Scientific Robustness and Consistency with International Standards*. Publication of the Association of the German Biofuel Industry, Berlin, Germany. Available at: http://www.fediol.eu/data/RZ_VDB_0030_Vorstudie_ENG_Komplett.pdf (accessed April 2014).

Fischedick M, Schaeffer R, Adedoyin A, Akai M, Bruckner T, Clarke L, Wright R (2011). Mitigation Potential and Costs. In *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation* (eds Edenhofer O, Pichs-Madruga R, Sokona Y, Seyboth K, Matschoss P, Kadner S, Zwickel T, Eickemeier P, Hansen G, Schlömer S, Von Stechow C), pp. 791–864. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Fischer G, Prieler S, Van Velthuizen H, Berndes G, Faaij A, Londo M, De Wit M (2010) Biofuel production potentials in Europe: sustainable use of cultivated land and pastures, Part II: land use scenarios. *Biomass and Bioenergy*, **34**, 173–187.

Fuglestvedt J, Shine K, Berntsen T, Cook J, Lee D, Stenke A, Waitz I (2010) Transport impacts on atmosphere and climate: metrics. *Atmospheric Environment*, **44**, 4648–4677.

Garcia-Frapolli E, Schilmann A, Berrueta V, Riojas-Rodriguez H, Edwards R, Johnson M, Masera O (2010) Beyond fuelwood savings: valuing the economic benefits of introducing improved biomass cookstoves in the Purépecha region of Mexico. *Ecological Economics*, **69**, 2598–2605.

Garcia-Ulloa J, Sloan S, Pacheco P, Ghazoul J, Koh LP (2012) Lowering environmental costs of oil-palm expansion in Colombia. *Conservation Letters*, **5**, 366–375.

Garg KK, Karlberg L, Wani SP, Berndes G (2011a) Jatropha production on wastelands in India: opportunities and trade-offs for soil and water management at the watershed scale. *Biofuels Bioproducts & Biorefining-Biofpr*, **5**, 410–430.

Garg K, Karlberg L, Wani S, Berndes G (2011b) Biofuel production on wastelands in India: opportunities and trade-offs for soil and water management at the watershed scale. *Biofuels, Bioproducts and Biorefining*, **5**, 410–430.

Gasparatos A, Stromberg P, Takeuchi K (2011) Biofuels, ecosystem services and human wellbeing: putting biofuels in the ecosystem services narrative. *Agriculture, Ecosystems & Environment*, **142**, 111–128.

Gawel E, Ludwig G (2011) The iLUC dilemma: how to deal with indirect land use changes when governing energy crops? *Land Use Policy*, **28**, 846–856.

GEA (2012). *Global Energy Assessment - Toward a Sustainable Future*. Cambridge University Press, International Institute for Applied Systems Analysis, Laxenburg, Austria, Cambridge, UK and New York, NY, USA.

Gelfand I, Sahajpal R, Zhang X, Izaurralde R, Gross K, Robertson G (2013) Sustainable bioenergy production from marginal lands in the US Midwest. *Nature*, **493**, 514–517.

Georgescu M, Lobell D, Field C (2011) Direct climate effects of perennial bioenergy crops in the United States. *Proceedings of the National Academy of Sciences*, **108**, 4307–4312.

Gerbens-Leenes W, Hoekstra A, Van der Meer T (2009) The water footprint of bioenergy. *Proceedings of the National Academy of Sciences*, **106**, 10219–10223.

German L, Schoneveld G (2012) A review of social sustainability considerations among EU-approved voluntary schemes for biofuels, with implications for rural livelihoods. *Energy Policy*, **51**, 765–778.

German L, Schoneveld G, Gumbo D (2011) The local social and environmental impacts of smallholder-based biofuel investments in Zambia. *Ecology and Society*, **16**, 12. doi: 10.5751/es-04280-160412.

German L, Schoneveld G, Mwangi E (2013) Contemporary processes of large-scale land acquisition in sub-Saharan Africa: legal deficiency or elite capture of the rule of law? *World Development*, **48**, 1–18.

Gibbs H, Johnston M, Foley J, Holloway T, Monfreda C, Ramankutty N, Zaks D (2008) Carbon payback times for crop-based biofuel expansion in the tropics: the effects of changing yield and technology. *Environmental Research Letters*, **3**, 034001.

Gohin A (2008) Impacts of the European biofuel policy on the farm sector: a general equilibrium assessment. *Applied Economic Perspectives and Policy*, **30**, 623–641.

Goldemberg J (2007) Ethanol for a sustainable energy future. *Science*, **315**, 808–810.

Gollakota S, McDonald S (2012) CO2 capture from ethanol production and storage into the Mt Simon Sandstone. *Greenhouse Gases: Science and Technology*, **2**, 346–351.

Gopalakrishnan G, Negri M, Wang M, Wu M, Snyder S, Lafreniere L (2009) Biofuels, land and water: a systems approach to sustainability. *Environmental Science & Technology*, **43**, 6094–6100.

Gopalakrishnan G, Negri M, Snyder S (2011a) A novel framework to classify marginal land for sustainable biomass feedstock production. *Journal of Environmental Quality*, **40**, 1593–1600.

Gopalakrishnan G, Negri M, Snyder S (2011b) Redesigning agricultural landscapes for sustainability using bioenergy crops: quantifying the tradeoffs between agriculture, energy and the environment. *Aspects of Applied Biology*, **112**, 139–146.

Gopalakrishnan G, Negri M, Salas W (2012) Modeling biogeochemical impacts of bioenergy buffers with perennial grasses for a row-crop field in Illinois. *GCB Bioenergy*, **4**, 739–750.

Gregg J, Smith S (2010) Global and regional potential for bioenergy from agricultural and forestry residue biomass. *Mitigation and Adaptation Strategies for Global Change*, **15**, 241–262.

Groom M, Gray E, Townsend P (2008) Biofuels and biodiversity: principles for creating better policies for biofuel production. *Conservation Biology*, **22**, 602–609.

Guest G, Bright R, Cherubini F, Strømman A (2013) Consistent quantification of climate impacts due to biogenic carbon storage across a range of bio-product systems. *Environmental Impact Assessment Review*, **43**, 21–30.

Gurung A, Oh SE (2013) Conversion of traditional biomass into modern bioenergy systems: a review in context to improve the energy situation in Nepal. *Renewable Energy*, **50**, 206–213.

Haberl H (2013) Net land-atmosphere flows of biogenic carbon related to bioenergy: towards an understanding of systemic feedbacks. *GCB Bioenergy*, **5**, 351–357.

Haberl H, Beringer T, Bhattacharya S, Erb K, Hoogwijk M (2010) The global technical potential of bio-energy in 2050 considering sustainability constraints. *Current Opinion in Environmental Sustainability*, **2**, 394–403.

Haberl H, Erb K, Krausmann F, Bondeau A, Lauk C, Müller C, Steinberger J (2011) Global bioenergy potentials from agricultural land in 2050: sensitivity to climate change, diets and yields. *Biomass and Bioenergy*, **35**, 4753–4769.

Haberl H, Sprinz D, Bonazountas M, Cocco P, Desaubies Y, Henze M, Searchinger T (2012) Correcting a fundamental error in greenhouse gas accounting related to bioenergy. *Energy Policy*, **45**, 18–23.

Haberl H, Mbow C, Deng X, Irwin EG, Kerr S, Kuemmerle T, Turner BL II (2013a). Finite Land Resources and Competition. In *Rethinking Global Land Use in an Urban Era*, (eds Seto KC, Reenberg A), pp. 33–67. MIT Press, Cambridge, MA. Available at: http://mitpress.mit.edu/books/rethinking-global-land-use-urban-era (accessed April 2014).

Haberl H, Schulze E, Körner C, Law B, Holtsmark B, Luyssaert S (2013b) Response: complexities of sustainable forest use. *GCB Bioenergy*, **5**, 1–2.

Haberl H, Erb KH, Krausmann F, Running S, Searchinger TD, Smith WK (2013c) Bioenergy: how much can we expect for 2050? *Environmental Research Letters*, **8**, 031004.

Hakala K, Kontturi M, Pahkala K (2009) Field biomass as global energy source. *Agricultural and Food Science*, **18**, 347–365.

Hall J, Matos S, Severino L, Beltrão N (2009) Brazilian biofuels and social exclusion: established and concentrated ethanol versus emerging and dispersed biodiesel. *Journal of Cleaner Production*, **17**(Suppl. 1), S77–S85.

Hallgren W, Schlosser CA, Monier E, Kicklighter D, Sokolov A, Melillo J (2013) Climate impacts of a large-scale biofuels expansion. *Geophysical Research Letters*, **40**, 1624–1630.

Hamelinck C, Faaij A (2006) Outlook for advanced biofuels. *Energy Policy*, **34**, 3268–3283.

Hanff E, Dabat M-H, Blin J (2011) Are biofuels an efficient technology for generating sustainable development in oil-dependent African nations? A macroeconomic assessment of the opportunities and impacts in Burkina Faso. *Renewable and Sustainable Energy Reviews*, **15**, 2199–2209.

Harper RJ, Sochacki SJ, Smettem KRJ, Robinson N (2010) Bioenergy feedstock potential from short-rotation woody crops in a dryland environment†. *Energy & Fuels*, **24**, 225–231.

Havlík P, Schneider U, Schmid E, Böttcher H, Fritz S, Skalský R, Obersteiner M (2011) Global land-use implications of first and second generation biofuel targets. *Energy Policy*, **39**, 5690–5702.

Herreras Martínez S, van Eijck J, Pereira da Cunha M, Guilhoto JJ, Walter A, Faaij A (2013) Analysis of socio-economic impacts of sustainable sugarcane–ethanol pro-

duction by means of inter-regional Input-Output analysis: Demonstrated for Northeast Brazil. *Renewable and Sustainable Energy Reviews*, **28**, 290–316.

Hertel T, Golub A, Jones A, O'Hare M, Plevin R, Kammen D (2010) Global land use and greenhouse gas emissions impacts of US Maize ethanol: estimating market-mediated responses. *BioScience*, **60**, 223–231.

Hochman G, Rajagopal D, Zilberman D (2010) The effect of biofuels on crude oil markets. *AgBioForum*, **13**, 112–118.

Hoefnagels R, Banse M, Dornburg V, Faaij A (2013) Macro-economic impact of large-scale deployment of biomass resources for energy and materials on a national level—A combined approach for the Netherlands. *Energy Policy*, **59**, 727–744.

Holtsmark B (2012) Harvesting in boreal forests and the biofuel carbon debt. *Climatic Change*, **112**, 415–428.

Holtsmark B (2013) The outcome is in the assumptions: analyzing the effects on atmospheric CO2 levels of increased use of bioenergy from forest biomass. *GCB Bioenergy*, **5**, 467–473.

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

Hoogwijk M, Faaij A, De Vries B, Turkenburg W (2009) Exploration of regional and global cost-supply curves of biomass energy from short-rotation crops at abandoned cropland and rest land under four IPCC SRES land-use scenarios. *Biomass and Bioenergy*, **33**, 26–43.

House J, Colin Prentice I, Le Quéré C (2002) Maximum impacts of future reforestation or deforestation on atmospheric CO2. *Global Change Biology*, **8**, 1047–1052.

Hsu D, Inman D, Heath G, Wolfrum E, Mann M, Aden A (2010) Life cycle environmental impacts of selected US ethanol production and use pathways in 2022. *Environmental Science & Technology*, **44**, 5289–5297.

Huang J, Yang J, Msangi S, Rozelle S, Weersink A (2012) Biofuels and the poor: global impact pathways of biofuels on agricultural markets. *Food Policy*, **37**, 439–451.

Hudiburg T, Law B, Wirth C, Luyssaert S (2011) Regional carbon dioxide implications of forest bioenergy production. *Nature Climate Change*, **1**, 419–423.

Hunsberger C, Bolwig S, Corbera E, Creutzig F (2013) Livelihood impacts of biofuel crop production: implications for governance. *Geoforum*, **54**, 248–260.

IEA (2010). *Sustainable Production of Second-Generation Biofuels: Potential and Perspectives in Major Economies and Developing Countries*. International Energy Agency, Paris.

IEA (2011). *Energy for All: Financing access for the poor. Special early excerpt of the World Energy Outlook 2011*. OECD/IEA, France, Paris.

IEA (2012) *Technology Roadmaps Bioenergy for Heat and Power*. OECD/IEA, France, Paris.

IEA (2013). IEA. Available at: https://www.google.de/search?q=IEA+2013&ie=utf-8&oe=utf-8&aq=t&rls=org.mozilla:de:official&client=firefox-a (accessed April 2014).

Immerzeel D, Verweij P, Hilst F, Faaij AP (2014) Biodiversity impacts of bioenergy crop production: a state-of-the-art review. *GCB Bioenergy*, **6**, 183–209.

Jackson R, Randerson J, Canadell J, Anderson R, Avissar R, Baldocchi D, Pataki D (2008) Protecting climate with forests. *Environmental Research Letters*, **3**, 044006.

Jaramillo P, Griffin W, Matthews H (2008) Comparative analysis of the production costs and life-cycle GHG emissions of FT liquid fuels from coal and natural gas. *Environmental Science & Technology*, **42**, 7559–7565.

Jerneck A, Olsson L (2013) A smoke-free kitchen: initiating community based co-production for cleaner cooking and cuts in carbon emissions. *Journal of Cleaner Production*, **60**, 208–215.

Jetter J, Zhao Y, Smith K, Khan B, Yelverton T, DeCarlo P, Hays M (2012) Pollutant emissions and energy efficiency under controlled conditions for household biomass cookstoves and implications for metrics useful in setting international test standards. *Environmental Science & Technology*, **46**, 10827–10834.

Johansson T, Nakicenovic N, Patwardhan A, Gomez-Echeverri L, Turkenburg W (2012). Summary for policymakers. In: *Global Energy Assessment - Toward a Sustainable Future* (eds Johansson TB, Nakicenovic N, Patwardhan A, Gomez-Echeverri L), pp. 3–30. Cambridge University Press, International Institute for Applied Systems Analysis, Laxenburg, Austria, Cambridge, UK and New York, NY.

Johnston M, Foley J, Holloway T, Kucharik C, Monfreda C (2009) Resetting global expectations from agricultural biofuels. *Environmental Research Letters*, **4**, 014004.

Johnston M, Licker R, Foley J, Holloway T, Mueller N, Barford C, Kucharik C. (2011). Closing the gap: global potential for increasing biofuel production through agricultural intensification. *Environmental Research Letters*, **6**, 034028.

Jonker J, Faaij A. (2013). Techno-economic assessment of micro-algae as feedstock for renewable bio-energy production. *Applied Energy*, **102**, 461–475.

Jonker J, Junginger M, Faaij A. (2013). Carbon payback period and carbon offset parity point of wood pellet production in the South-eastern United States. *GCB Bioenergy*, **6**, 371–389. doi: 10.1111/gcbb.12056

Joos F, Roth R, Fuglestvedt J, Peters G, Enting I, Von Bloh W, Weaver A (2013) Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis. *Atmospheric Chemistry and Physics Discussions*, **12**, 19799–19869.

Junginger M, Goh CS, Faaij A (eds) (2014) *International Bioenergy Trade: History, Status & Outlook on Securing Sustainable Bioenergy Supply, Demand and Markets*. Springer, Dordrecht, Netherlands.

Kaiser E, Ruser R (2000) Nitrous oxide emissions from arable soils in Germany — An evaluation of six long-term field experiments. *Journal of Plant Nutrition and Soil Science*, **163**, 249–259.

Kar A, Rehman I, Burney J, Puppala S, Suresh R, Singh L, Ramanathan V (2012) Real-time assessment of black carbon pollution in Indian households due to traditional and improved biomass cookstoves. *Environmental Science & Technology*, **46**, 2993–3000.

Karlsson H, Byström L. (2011). *Global Status of BECCS Projects 2010*. Global CCS Institute & Biorecro AB.

Keating B, Carberry P, Dixon J. (2013). Agricultural intensification and the food security challenge in Sub Saharan Africa. In *Agro-Ecological Intensification of Agricultural Systems in the African Highlands* (eds Vanlauwe B, Van Asten P, Blomme G), pp. 20–35. Routledge, New York.

Khanna M, Crago C, Black M (2011) Can biofuels be a solution to climate change? The implications of land use change-related emissions for policy. *Interface Focus*, **1**, 233–247.

Kløverpris J, Mueller S (2013) Baseline time accounting: considering global land use dynamics when estimating the climate impact of indirect land use change caused by biofuels. *The International Journal of Life Cycle Assessment*, **18**, 319–330.

Kochsiek A, Knops J (2012) Maize cellulosic biofuels: soil carbon loss can be a hidden cost of residue removal. *GCB Bioenergy*, **4**, 229–233.

Koh LP, Wilcove DS (2008) Is oil palm agriculture really destroying tropical biodiversity? *Conservation Letters*, **1**, 60–64.

Koizumi T (2013) Biofuel and food security in China and Japan. *Renewable and Sustainable Energy Reviews*, **21**, 102–109.

Koornneef J, Van Breevoort P, Hamelinck C, Hendriks C, Hoogwijk M, Koop K, Camps A (2012) Global potential for biomass and carbon dioxide capture, transport and storage up to 2050. *International Journal of Greenhouse Gas Control*, **11**, 117–132.

Koornneef J, Van Breevoort P, Noothout P, Hendriks C, Luning U, Camps A. (2013). Global potential for biomethane production with carbon capture, transport and storage up to 2050 GHGT-11. *Energy Procedia*, **37**, 6043–6052.

Körner C (2006) Plant CO2 responses: an issue of definition, time and resource supply. *New Phytologist*, **172**, 393–411.

Kriegler E, Edenhofer O, Reuster L, Luderer G, Klein D (2013) Is atmospheric carbon dioxide removal a game changer for climate change mitigation? *Climatic Change*, **118**, 45–57.

Kyu HH, Georgiades K, Boyle MH (2010) Biofuel smoke and child anemia in 29 developing countries: a multilevel analysis. *Annals of Epidemiology*, **20**, 811–817.

Lal R (2010) Managing soils for a warming earth in a food-insecure and energy-starved world. *Journal of Plant Nutrition and Soil Science*, **173**, 4–15.

Lam MK, Tan KT, Lee KT, Mohamed AR (2009) Malaysian palm oil: surviving the food versus fuel dispute for a sustainable future. *Renewable and Sustainable Energy Reviews*, **13**, 1456–1464.

Lamers P, Junginger M (2013) The 'debt' is in the detail: a synthesis of recent temporal forest carbon analyses on woody biomass for energy. *Biofuels: Bioproducts and Biorefining*, **7**, 373–385.

Lamers P, Junginger H, Dymond C, Faaij A. (2013). Damaged forests provide an opportunity to mitigate climate change. *GCB Bioenergy*, **6**, 44–60.

Langeveld J, Dixon J, Van Keulen H, Quist-Wessel P (2013) *Analyzing the Effect of Biofuel Expansion on Land Use in Major Producing Countries: Evidence of Increased Multiple Cropping*. Biofuels, Bioproducts and Biorefining.

Larson E, Li Z, Williams R (2012) Chapter 12 - fossil energy. In: *Global Energy Assessment - Toward a Sustainable Future* (eds Johansson TB, Nakicenovic N, Patwardhan A, Gomez-Echeverri L), pp. 901–992. Cambridge University Press, the International Institute for Applied Systems Analysis, Laxenburg, Austria, Cambridge, UK and New York, NY, USA.

Latta G, Baker J, Beach R, Rose S, McCarl B (2013) A multi-sector intertemporal optimization approach to assess the GHG implications of US forest and agricultural biomass electricity expansion. *Journal of Forest Economics*, **19**, 361–383.

Lee S, Lee S, Lee D. (2013). Design and development of synthetic microbial platform cells for bioenergy. *Frontiers in Microbiology*, **4**, 92.

Lenton T, Vaughan N (2009) The radiative forcing potential of different climate geoengineering options. *Atmospheric Chemistry and Physics*, **9**, 5539–5561.

Li H, Cann A, Liao J (2010) Biofuels: biomolecular engineering fundamentals and advances. *Annual Review of Chemical and Biomolecular Engineering*, **1**, 19–36.

Liao J, Messing J (2012) Energy biotechnology. *Current Opinion in Biotechnology*, **23**, 287–289.

Lim S, Vos T, Flaxman A *et al.* (2012) A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the global burden of disease study 2010. *The Lancet*, **380**, 2224–2260.

Lippke B, Oneil E, Harrison R, Skog K, Gustavsson L, Sathre R (2011) Life cycle impacts of forest management and wood utilization on carbon mitigation: knowns and unknowns. *Carbon Management*, **2**, 303–333.

Lisboa C, Butterbach-Bahl K, Mauder M, Kiese R (2011) Bioethanol production from sugarcane and emissions of greenhouse gases – known and unknowns. *GCB Bioenergy*, **3**, 277–292.

Liska A, Perrin R (2009) Indirect land use emissions in the life cycle of biofuels: regulations vs science. *Biofuels, Bioproducts and Biorefining*, **3**, 318–328.

Liu G, Larson E, Williams R, Kreutz T, Guo X (2010) Making Fischer– Tropsch fuels and electricity from coal and biomass: performance and cost analysis. *Energy & Fuels*, **25**, 415–437.

Liu G, Williams R, Larson E, Kreutz T (2011) Design/economics of low-carbon power generation from natural gas and biomass with synthetic fuels co-production. *Energy Procedia*, **4**, 1989–1996.

Loarie S, Lobell D, Asner G, Mu Q, Field C (2011) Direct impacts on local climate of sugar-cane expansion in Brazil. *Nature Climate Change*, **1**, 105–109.

Lohila A, Minkkinen K, Laine J, Savolainen I, Tuovinen J, Korhonen L, Laaksonen A (2010) Forestation of boreal peatlands: impacts of changing albedo and greenhouse gas fluxes on radiative forcing. *Journal of Geophysical Research*, **115**, G04011. doi: 10.1029/2010JG001327.

Lotze-Campen H, Lampe M, Von Kyle P, Fujimori S, Havlík P, Van Meijl H, Wise M. (2013). Impacts of increased bioenergy demand on global food markets: an AgMIP economic model intercomparison. *Agricultural Economics*, **45**, 103–116.

Loudermilk E, Scheller R, Weisberg P, Yang J, Dilts T, Karam S, Skinner C (2013) Carbon dynamics in the future forest: the importance of long-term successional legacy and climate–fire interactions. *Global Change Biology*, **19**, 3502–3515.

Lundmark T, Bergh J, Hofer P, Lundström A, Nordin A, Poudel BC, Werner F (2014) Potential roles of Swedish forestry in the context of climate change mitigation. *Forests*, **5**, 557–578.

Lynd L, Aziz R, De Brito Cruz C *et al.* (2011) A global conversation about energy from biomass: the continental conventions of the global sustainable bioenergy project. *Interface Focus*, **1**, 271–279.

Lywood W, Pinkney J, Cockerill S (2009) Impact of protein concentrate coproducts on net land requirement for European biofuel production. *GCB Bioenergy*, **1**, 346–359.

Macedo I, Seabra J, Silva J (2008) Green house gases emissions in the production and use of ethanol from sugarcane in Brazil: the 2005/2006 averages and a prediction for 2020. *Biomass and Bioenergy*, **32**, 582–595.

Mackey B, Prentice I, Steffen W, House J, Lindenmayer D, Keith H, Berry S (2013) Untangling the confusion around land carbon science and climate change mitigation policy. *Nature Climate Change*, **3**, 552–557.

Madlener R, Robledo C, Muys B, Freja JTB (2006) A sustainability framework for enhancing the long-term success of lulucf projects. *Climatic Change*, **75**, 241–271.

Marland G, Schlamadinger B (1995) Biomass fuels and forest-management strategies: how do we calculate the greenhouse-gas emissions benefits? *Energy*, **20**, 1131–1140.

Marland G, Pielke R, Apps M, Avissar R, Betts R, Davis K, Xue Y (2003) The climatic impacts of land surface change and carbon management, and the implications for climate-change mitigation policy. *Climate Policy*, **3**, 149–157.

Martin WJ, Glass R, Balbus J, Collins F (2011) A major environmental cause of death. *Science*, **334**, 180–181.

Martinelli LA, Filoso S (2008) Expansion of sugarcane ethanol production in Brazil: environmental and social challenges. *Ecological Applications: A Publication of the Ecological Society of America*, **18**, 885–898.

McKechnie J, Colombo S, Chen J, Mabee W, MacLean H (2011) Forest bioenergy or forest carbon? assessing trade-offs in greenhouse gas mitigation with wood-based fuels. *Environmental Science & Technology*, **45**, 789–795.

McLaren D (2012) A comparative global assessment of potential negative emissions technologies. *Special Issue: Negative Emissions Technology*, **90**, 489–500.

Meerman J, Ramirez A, Turkenburg W, Faaij A (2011) Performance of simulated flexible integrated gasification polygeneration facilities. Part A: a technical-energetic assessment. *Renewable and Sustainable Energy Reviews*, **15**, 2563–2587.

Meerman J, Ramírez A, Turkenburg W, Faaij A (2012) Performance of simulated flexible integrated gasification polygeneration facilities, Part B: economic evaluation. *Renewable and Sustainable Energy Reviews*, **16**, 6083–6102.

Meier D, Van de Beld B, Bridgwater A, Elliott D, Oasmaa A, Preto F (2013) State-of-the-art of fast pyrolysis in IEA bioenergy member countries. *Renewable and Sustainable Energy Reviews*, **20**, 619–641.

Melillo JM, Reilly JM, Kicklighter DW, Gurgel AC, Cronin TW, Paltsev S, Schlosser CA (2009) Indirect emissions from biofuels: how important? *Science*, **326**, 1397–1399.

Mingorría S, Gamboa G, Alonso-Fradejas A (2010) *Metabolismo socio-ecológico de comunidades campesinas Q'eqchi' y la expansión de la agro-industria de caña de azúcar y palma Africana : Valle del Río Polochic, Guatemala*. Instituto de Ciencia y Technología Ambientales and Instituto de Estudios Agrarios y Rurales, Barcelona and Mexico.

Mingorría S, Gamboa G, Martín-López B, Corbera E (2014) The oil palm boom: socio-economic implications for Q'eqchi' communities in the Polochic valley, Guatemala. *Environment, Development and Sustainability*, 1–31.

Muys B, Norgrove L, Alamirew T, Birech R, Chirinian E, Delelegn Y, Zetina R (2014) Integrating mitigation and adaptation into development: the case of Jatropha curcas in sub-Saharan Africa. *GCB Bioenergy*, **6**, 169–171.

Mwakaje AG (2012) Can Tanzania realise rural development through biofuel plantations? Insights from the study in Rufiji District. *Energy for Sustainable Development*, **16**, 320–327.

Myhre G, Shindell D (2013) Anthropogenic and Natural Radiative Forcing In: IPCC WGI Fifth Assessment Report.

Nabuurs J, Masera O, Andrasko K, Benitez-Ponce P, Boer R, Dutschke M, Zhang X (2007) Chapter 9, Forestry. IPCC Fourth Assessment Report. IPCC.

Nabuurs G, Lindner M, Verkerk P, Gunia K, Deda P, Michalak R, Grassi G. (2013). First signs of carbon sink saturation in European forest biomass. *Nature Climate Change*, **3**, 792–796.

Nassar A, Harfuch L, Bachion L, Moreira M (2011) Biofuels and land-use changes: searching for the top model. *Interface Focus*, **1**, 224–232.

Nijsen M, Smeets E, Stehfest E, Van Vuuren D (2012) An evaluation of the global potential of bioenergy production on degraded lands. *GCB Bioenergy*, **4**, 130–147.

Oberling DF, Obermaier M, Szklo A, La Rovere EL (2012) Investments of oil majors in liquid biofuels: the role of diversification, integration and technological lock-ins. *Biomass and Bioenergy*, **46**, 270–281.

O'Halloran T, Law B, Goulden M, Wang Z, Barr J, Schaaf C, Engel V (2012) Radiative forcing of natural forest disturbances. *Global Change Biology*, **18**, 555–565.

O'Hare M, Plevin R, Martin J, Jones A, Kendall A, Hopson E (2009) Proper accounting for time increases crop-based biofuels' greenhouse gas deficit versus petroleum. *Environmental Research Letters*, **4**, 024001.

O'Shaughnessy SM, Deasy MJ, Kinsella CE, Doyle JV, Robinson AJ (2013) Small scale electricity generation from a portable biomass cookstove: prototype design and preliminary results. *Applied Energy*, **102**, 374–385.

Pacca S, Moreira JR (2011) A biorefinery for mobility? *Environmental Science & Technology*, **45**, 9498–9505.

Pan Y, Birdsey R, Fang J, Houghton R, Kauppi P, Kurz W, Aber J (2011) A large and persistent carbon sink in the world's forests. *Science*, **333**, 988–993.

Parish E, Hilliard M, Baskaran L, Dale V, Griffiths N, Mulholland P, Middleton R (2012) Multimetric spatial optimization of switchgrass plantings across a watershed. *Biofuels, Bioproducts and Biorefining*, **6**, 58–72.

Peralta-Yahya P, Zhang F, Del Cardayre S, Keasling J (2012) Microbial engineering for the production of advanced biofuels. *Nature*, **488**, 320–328.

Pielke R, Pitman A, Niyogi D, Mahmood R, McAlpine C, Hossain F, Fall S (2011) Land use/land cover changes and climate: modeling analysis and observational evidence. *Wiley Interdisciplinary Reviews: Climate Change*, **2**, 828–850.

Pingoud K, Ekholm T, Savolainen I (2012) Global warming potential factors and warming payback time as climate indicators of forest biomass use. *Mitigation and Adaptation Strategies for Global Change*, **17**, 369–386.

Plattner G, Stocker T, Midgley P, Tignor M (2009) *IPCC expert meeting on the science of alternative metrics*. IPCC Working Group I Technical Support Unit, Bern.

Plevin R, O'Hare M, Jones A, Torn M, Gibbs H (2010) Greenhouse gas emissions from biofuels: indirect land use change are uncertain but may be much greater than previously estimated. *Environmental Science & Technology*, **44**, 8015–8021.

Plevin R, Delucchi M, Creutzig F. (2013). Using attributional life cycle assessment to estimate climate-change mitigation benefits misleads policy makers. *Journal of Industrial Ecology*, n/a–n/a. doi: 10.1111/jiec.12074

Popp A, Dietrich JP, Lotze-Campen H, Klein D, Bauer N, Krause M, Edenhofer O (2011) The economic potential of bioenergy for climate change mitigation with special attention given to implications for the land system. *Environmental Research Letters*, **6**, 34–44.

Popp A, Rose S, Calvin K, Van Vuuren D, Dietrich J, Wise M, Kriegler E (2013) Land-use transition for bioenergy and climate stabilization: model comparison of drivers, impacts and interactions with other land use based mitigation options. *Climatic Change*, **123**, 495–509.

Rajagopal D, Hochman G, Zilberman D (2011) Indirect fuel use change (IFUC) and the lifecycle environmental impact of biofuel policies. *Energy Policy*, **39**, 228–233.

Randerson J, Liu H, Flanner M, Chambers S, Jin Y, Hess P, Zender C (2006) The impact of boreal forest fire on climate warming. *Science*, **314**, 1130–1132.

Reilly J, Melillo J, Cai Y, Kicklighter D, Gurgel A, Paltsev S, Schlosser A (2012) Using land to mitigate climate change: hitting the target, recognizing the trade-offs. *Environmental Science & Technology*, **46**, 5672–5679.

REN21 (2012). *Renewables 2012 Global Status Report*. Available at: www.ren21.net/gsr (accessed April 2014).

REN21 (2013) *Renewables 2013 Global Status Report*. Renewable Energy Policy Network for the 21st century, Paris, France.

Repo A, Tuomi M, Liski J (2011) Indirect carbon dioxide emissions from producing bioenergy from forest harvest residues. *GCB Bioenergy*, **3**, 107–115.

Repo A, Känkänen R, Tuovinen J, Antikainen R, Tuomi M, Vanhala P, Liski J (2012) Forest bioenergy climate impact can be improved by allocating forest residue removal. *GCB Bioenergy*, **4**, 202–212.

Rhodes J, Keith D (2008) Biomass with capture: negative emissions within social and environmental constraints: an editorial comment. *Climatic Change*, **87**, 321–328.

Robertson G, Vitousek P (2009) Nitrogen in agriculture: balancing the cost of an essential resource. *Annual Review of Environmental Resources*, **34**, 97–125.

Rogner H, Aguilera R, Archer C, Bertani R, Bhattacharya S, Dusseault M, Yakushev V. (2012). Chapter 7 - energy resources and potentials. In: *Global Energy Assessment - Toward a Sustainable Future* (eds Johansson TB, Nakicenovic N, Patwardhan A, Gomez-Echeverri L), pp. 423–512. Cambridge University Press, International Institute for Applied Systems Analysis, Laxenburg, Austria, Cambridge, UK and New York, NY, USA. Available at: www.globalenergyassessment.org (accessed April 2014).

Rose S, Ahammad H, Eickhout B, Fisher B, Kurosawa A, Rao S, Van Vuuren D (2012) Land-based mitigation in climate stabilization. *Energy Economics*, **34**, 365–380.

Rose S, Beach R, Calvin K, McCarl B, Petrusa J, Sohngen B, Wise M. (2013). *Estimating Global Greenhouse Gas Emissions Offset Supplies: Accounting for Investment Risks and Other Market Realties (No. 1025510)*. EPRI, Palo Alto, CA.

Rosillo-Calle F, Teelucksingh S, Thrän D, Seiffert M. (2012). *The Potential Role of Biofuels in Commercial Air Transport - Biojetfuel* (No. Task 40: Sustainable International Bioenergy trade). IEA, Paris.

Sala OE, Chapin FS, Armesto JJ, Berlow E, Bloomfield J, Dirzo R, Wall DH (2000) Global biodiversity scenarios for the year 2100. *Science*, **287**, 1770–1774.

Satolo L, Bacchi M. (2013). Impacts of the recent expansion of the sugarcane sector on municipal per capita income in São Paulo State. *ISRN Economics*, **2013**, 828169.

Sayer J, Ghazoul J, Nelson P, Klintuni Boedhihartono A (2012) Oil palm expansion transforms tropical landscapes and livelihoods. *Global Food Security*, **1**, 114–119.

Scheidel A, Sorman AH (2012) Energy transitions and the global land rush: ultimate drivers and persistent consequences. *Global Transformations, Social Metabolism and the Dynamics of Socio-Environmental Conflicts*, **22**, 588–595.

Schmidt J, Gass V, Schmid E (2011) Land use changes, greenhouse gas emissions and fossil fuel substitution of biofuels compared to bioelectricity production for electric cars in Austria. *Biomass and Bioenergy*, **35**, 4060–4074.

Schut M, Slingerland M, Locke A (2010) Biofuel developments in Mozambique. Update and analysis of policy, potential and reality. *Energy Policy*, **38**, 5151–5165.

Schwietzke S, Griffin W, Matthews H (2011) Relevance of emissions timing in biofuel greenhouse gases and climate impacts. *Environmental Science & Technology*, **45**, 8197–8203.

Scown C, Nazaroff W, Mishra U, Strogen B, Lobscheid A, Masanet E, McKone T (2012) Lifecycle greenhouse gas implications of US national scenarios for cellulosic ethanol production. *Environmental Research Letters*, **7**, 014011.

Seabra J, Macedo I, Chum H, Faroni C, Sarto C (2011) Life cycle assessment of Brazilian sugarcane products: GHG emissions and energy use. *Biofuels, Bioproducts and Biorefining*, **5**, 519–532.

Searchinger T (2010) Biofuels and the need for additional carbon. *Environmental Research Letters*, **5**, 024007.

Searchinger T, Heimlich R, Houghton R, Dong F, Elobeid A, Fabiosa J, Yu T. (2008). Use of US Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land Use Change. *Science*, **319**, 1238–1240

Searchinger T, Hamburg S, Melillo J, Chameides W, Havlik P, Kammen D, Tilman D (2009) Fixing a critical climate accounting error. *Science*, **326**, 527–528.

Sedjo R, Tian X (2012) Does wood bioenergy increase carbon stocks in forests? *Journal of Forestry*, **110**, 304–311.

Selfa T, Kulcsar L, Bain C, Goe R, Middendorf G (2011) Biofuels bonanza?: exploring community perceptions of the promises and perils of biofuels production. *Biomass and Bioenergy*, **35**, 1379–1389.

Senel O, Chugunov N (2013) CO2 injection in a saline formation: pre-injection reservoir modeling and uncertainty analysis for illinois basin–decatur project. *Energy Procedia*, **37**, 4598–4611.

Serrano-Ruiz J, West R, Dumesic J (2010) Catalytic conversion of renewable biomass resources to fuels and chemicals. *Annual Review of Chemical and Biomolecular Engineering*, **1**, 79–100.

Shen H, Poovaiah C, Ziebell A, Tschaplinski T, Pattathil S, Gjersing E, Dixon R. (2013). Enhanced characteristics of genetically modified switchgrass (Panicum virgatum L.) for high biofuel production. *Biotechnology for Biofuels*, **6**, 71.

Smeets E, Faaij A (2007) Bioenergy potentials from forestry in 2050. *Climatic Change*, **81**, 353–390.

Smeets E, Faaij A (2010) The impact of sustainability criteria on the costs and potentials of bioenergy production–Applied for case studies in Brazil and Ukraine. *Biomass and Bioenergy*, **34**, 319–333.

Smeets E, Faaij A, Lewandowski I, Turkenburg W (2007) A bottom-up assessment and review of global bio-energy potentials to 2050. *Progress in Energy and Combustion Science*, **33**, 56–106.

Smeets E, Junginger M, Faaij A, Walter A, Dolzan P, Turkenburg W (2008) The sustainability of Brazilian ethanol—an assessment of the possibilities of certified production. *Biomass and Bioenergy*, **32**, 781–813.

Smeets E, Bouwman L, Stehfest E, van Vuuren D, Posthuma A (2009) Contribution of N2O to the greenhouse gas balance of first-generation biofuels. *Global Change Biology*, **15**, 780–780.

Smith P (2005) An overview of the permanence of soil organic carbon stocks: influence of direct human-induced, indirect and natural effects. *European Journal of Soil Science*, **56**, 673–680.

Smith KA, Searchinger TD (2012) Crop-based biofuels and associated environmental concerns. *GCB Bioenergy*, **4**, 479–484.

Smith L, Torn M (2013) Ecological limits to terrestrial biological carbon dioxide removal. *Climatic Change*, **118**, 89–103.

Smith WK, Zhao M, Running SW (2012a) Global bioenergy capacity as constrained by observed biospheric productivity rates. *BioScience*, **62**, 911–922.

Smith K, Mosier A, Crutzen P, Winiwarter W (2012b) The role of N2O derived from crop-based biofuels, and from agriculture in general, in Earth's climate. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **367**, 1169–1174.

Smith P, Bustamente M, Ahammad H, Clark H, Dong H, Elsiddig E, Tubiello F (2014). Agriculture, forestry and other land use (AFOLU). In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K, Adler A, Baum I, Brunner S, Eickemeier P, Kriemann B, Savolainen J, Schlömer S, Von Stechow C, Zwickel T, Minx J), pp. 1–179. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Sochacki S, Harper R, Smettem K (2012) Bio-mitigation of carbon following afforestation of abandoned salinized farmland. *GCB Bioenergy*, **4**, 193–201.

Sparovek G, Berndes G, Egeskog A, De Freitas F, Gustafsson S, Hansson J (2007) Sugarcane ethanol production in Brazil: an expansion model sensitive to socioeconomic and environmental concerns. *Biofuels, Bioproducts and Biorefining*, **1**, 270–282.

Spath P, Mann M (2004). Biomass Power and Conventional Fossil Systems with and without CO2 Sequestration – Comparing the Energy Balance, Greenhouse Gas Emissions and Economics. Available at: http://www.nrel.gov/docs/fy04osti/32575.pdf (accessed April 2014).

SREX, I. P. on C. C. (2012) *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaption*. Cambridge University Press, New York, N.Y.

Steenblik R (2007). *Biofuels - At What Cost? Government Support for Ethanol in Selected OECD* (p. 82). International Institute for sustainable Development, Winnipeg, Canada. Available at: http://www.iisd.org/publications/pub.aspx?id=895 (accessed April 2014).

Sterner M, Fritsche U (2011) Greenhouse gas balances and mitigation costs of 70 modern Germany-focused and 4 traditional biomass pathways including land-use change effects. *Biomass and Bioenergy*, **35**, 4797–4814.

Stromberg P, Gasparatos A (2012). Biofuels at the confluence of energy security, rural development and food security: a developing country perspective. In: *Socio-*

Economic and Environmental Impacts of Biofuels. Evidence from Developing Countries (eds Gasparatos A, Stromberg P), pp. 1–375. Cambridge University Press, Cambridge, UK and New York, USA.

Stupak I, Lattimore B, Titus B, Smith C (2011) Criteria and indicators for sustainable forest fuel production and harvesting: a review of current standards for sustainable forest management. *Biomass and Bioenergy*, **35**, 3287–3308.

Sumathi S, Chai SP, Mohamed AR (2008) Utilization of oil palm as a source of renewable energy in Malaysia. *Renewable and Sustainable Energy Reviews*, **12**, 2404–2421.

Sun A, Davis R, Starbuck M, Ben-Amotz A, Pate R, Pienkos P (2011) Comparative cost analysis of algal oil production for biofuels. *Energy*, **36**, 5169–5179.

Swann A, Fung I, Levis S, Bonan G, Doney S (2010) Changes in Arctic vegetation amplify high-latitude warming through the greenhouse effect. *Proceedings of the National Academy of Sciences*, **107**, 1295–1300.

Swann A, Fung I, Chiang J (2011) Mid-latitude afforestation shifts general circulation and tropical precipitation. *PNAS*, **109**, 712–716.

Taheripour F, Hertel T, Tyner W (2011) Implications of biofuels mandates for the global livestock industry: a computable general equilibrium analysis. *Agricultural Economics*, **42**, 325–342.

Tan KT, Lee KT, Mohamed AR, Bhatia S (2009) Palm oil: addressing issues and towards sustainable development. *Renewable and Sustainable Energy Reviews*, **13**, 420–427.

Tanaka K, Johansson D, O'Neill B, Fuglestvedt J (2013). Emission metrics under the 2° C climate stabilization target. *Climatic Change*, **117**, 933–941.

Tavoni M, Socolow R (2013) Modeling meets science and technology: an introduction to a special issue on negative emissions. *Climatic Change*, **118**, 1–14.

Thompson MC, Baruah M, Carr ER (2011a) Seeing REDD+ as a project of environmental governance. *Environmental Science & Policy*, **14**, 100–110.

Thompson W, Whistance J, Meyer S (2011b) Effects of US biofuel policies on US and world petroleum product markets with consequences for greenhouse gas emissions. *Energy Policy*, **39**, 5509–5518.

Tilman D, Hill J, Lehman C (2006) Carbon-negative biofuels from low-input high-diversity grassland biomass. *Science*, **314**, 1598–1600.

Tilman D, Socolow R, Foley JA, Hill J, Larson E, Lynd L, Williams R (2009) Beneficial biofuels-the food, energy, and environment trilemma. *Science*, **325**, 270–271.

Timilsina G, Beghin J, Van der Mensbrugghe D, Mevel S (2012) The impacts of biofuels targets on land-use change and food supply: a global CGE assessment. *Agricultural Economics*, **43**, 315–332.

Triantafyllidis K, Lappas A, Stöcker M (2013). The Role of Catalysis for the Sustainable Production of Bio-fuels and Bio-chemicals. Access Online via Elsevier.

Tsao C, Campbell JE, Mena-Carrasco M, Spak SN, Carmichael GR, Chen Y (2012) Increased estimates of air-pollution emissions from Brazilian sugar-cane ethanol. *Nature Climate Change*, **2**, 53–57.

Turconi R, Boldrin A, Astrup T (2013) Life cycle assessment (LCA) of electricity generation technologies: overview, comparability and limitations. *Renewable and Sustainable Energy Reviews*, **28**, 555–565.

Turkenburg W, Arent D, Bertani R, Faaij A, Hand M, Krewitt W, Usher E (2012) Chapter 11 - renewable energy. In: *Global Energy Assessment - Toward a Sustainable Future* (eds Johansson TB, Nakicenovic N, Patwardhan A, Gomez-Echeverri L), pp. 761–900. Cambridge University Press, International Institute for Applied Systems Analysis, Laxenburg, Austria, Cambridge, UK and New York, NY, USA.

UNEP (2009) *Assessing Biofuels, Towards Sustainable Production and Use of Resources*. United Nations Environment Programme (UNEP), Division of Technology, Industry and Ecocnomics, Paris.

UNFCCC-CDM (2012). *CDM-SSC WG, Annex 8*. UNFCCC-CDM, Bonn.

Ürge-Vorsatz D, Eyre N, Graham P *et al.* (2012) Towards sustainable energy end-use: buildings chapter 10. In: *Global Energy Assessment* (eds Johansson TB, Nakicenovic N, Patwardhan A, Gomez-Echeverri L), Cambridge University Press, Cambridge.

US DOE (2011) *Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry*. Department of Energy, U.S.

Van Dam J, Faaij A, Hilbert J, Petruzzi H, Turkenburg W (2009a) Large-scale bioenergy production from soybeans and switchgrass in Argentina: part A: potential and economic feasibility for national and international markets. *Renewable and Sustainable Energy Reviews*, **13**, 1710–1733.

Van Dam J, Faaij A, Hilbert J, Petruzzi H, Turkenburg W (2009b) Large-scale bioenergy production from soybeans and switchgrass in Argentina: part B. Environmental and socio-economic impacts on a regional level. *Renewable and Sustainable Energy Reviews*, **13**, 1679–1709.

Van Dam J, Junginger M, Faaij A (2010) From the global efforts on certification of bioenergy towards an integrated approach based on sustainable land use planning. *Renewable and Sustainable Energy Reviews*, **14**, 2445–2472.

Van de Velde L, Verbeke W, Popp M, Buysse J, Van Huylenbroeck G (2009) Perceived importance of fuel characteristics and its match with consumer beliefs about biofuels in Belgium. *Energy Policy*, **37**, 3183–3193.

Van der Hilst F, Dornburg V, Sanders J, Elbersen B, Graves A, Turkenburg W, Faaij A (2010) Potential, spatial distribution and economic performance of regional biomass chains: the North of the Netherlands as example. *Agricultural Systems*, **103**, 403–417.

Van der Hilst F, Lesschen J, Van Dam J, Riksen M, Verweij P, Sanders J, Faaij A (2012a) Spatial variation of environmental impacts of regional biomass chains. *Renewable and Sustainable Energy Reviews*, **16**, 2053–2069.

Van der Hilst F, Van Dam J, Verweij P, Riksen M, Sanders J, Faaij A (2012b) Spatial variation in environmental impacts of bioenergy supply chains. *Renewable and Sustainable Energy Reviews*, **16**, 2053–2069.

Van der Hilst F, Verstegen J, Karssenberg D, Faaij A (2012c) Spatiotemporal land use modelling to assess land availability for energy crops–illustrated for Mozambique. *GCB Bioenergy*, **4**, 859–874.

Van der Horst D, Vermeylen S (2011) Spatial scale and social impacts of biofuel production. *Biomass and Bioenergy*, **35**, 2435–2443.

Van der Voet E, Lifset R, Luo L (2010) Life-cycle assessment of biofuels, convergence and divergence. *Biofuels*, **1**, 435–449.

Van Eijck J, Smeets E, Faaij A (2012) The economic performance of jatropha, cassava and Eucalyptus production systems for energy in an East African smallholder setting. *GCB Bioenergy*, **4**, 828–845.

Van Vliet O, Faaij A, Turkenburg W (2009) Fischer-Tropsch diesel production in a well-to-wheel perspective: a carbon, energy flow and cost analysis. *Energy Conversion and Management*, **50**, 855–876.

Van Vliet O, Brouwer A, Kuramochi T, Van Den Broek M, Faaij A (2011a) Energy use, cost and CO_2 emissions of electric cars. *Journal of Power Sources*, **196**, 2298–2310.

Van Vliet O, Van den Broek M, Turkenburg W, Faaij A (2011b) Combining hybrid cars and synthetic fuels with electricity generation and carbon capture and storage. *Energy Policy*, **39**, 248–268.

Van Vuuren D, Van Vliet J, Stehfest E (2009) Future bio-energy potential under various natural constraints. *Energy Policy*, **37**, 4220–4230.

Verdonk M, Dieperink C, Faaij A (2007) Governance of the emerging bio-energy markets. *Energy Policy*, **35**, 3909–3924.

Viana K, Perez R (2013). Survey of sugarcane industry in Minas Gerais, Brazil: focus on sustainability. *Biomass and Bioenergy*, **58**, 149–157.

Von Blottnitz H, Curran M (2007) A review of assessments conducted on bio-ethanol as a transportation fuel from a net energy, greenhouse gas, and environmental life cycle perspective. *Journal of Cleaner Production*, **15**, 607–619.

Von Geibler J (2013) Market-based governance for sustainability in value chains: conditions for successful standard setting in the palm oil sector. *Journal of Cleaner Production*, **56**, 39–53.

Von Maltitz GP, Setzkorn KA (2013) A typology of Southern African biofuel feedstock production projects. *Biomass and Bioenergy*, **59**, 33–59.

Walter A, Dolzan P, Quilodrán O, Garcia J, Da Silva C, Piacente F, Segerstedt A (2008) A sustainability Analysis of the Brazilian Ethanol. Report Submitted to the United Kingdom Embassy, Brazil.

Walter A, Dolzan P, Quilodrán O, De Oliveira J, Da Silva C, Piacente F, Segerstedt A (2011) Sustainability assessment of bio-ethanol production in Brazil considering land use change, GHG emissions and socio-economic aspects. *Energy Policy*, **39**, 5703–5716.

Wang M, Han J, Haq Z, Tyner W, Wu M, Elgowainy A (2011) Energy and greenhouse gas emission effects of corn and cellulosic ethanol with technology improvements and land use changes. *Biomass and Bioenergy*, **35**, 1885–1896.

Wang X, Franco J, Masera O, Troncoso K, Rivera M (2013) *What Have We Learned about Household Biomass Cooking in Central America?*. The Worldbank, Washington, DC.

Warner E, Zhang Y, Inman D, Heath G (2013). Challenges in the estimation of greenhouse gas emissions from biofuel-induced global land-use change. *Biofuels, Bioproducts and Biorefining*, **8**, 114–125.

Weightman R, Cottrill B, Wiltshire J, Kindred D, Sylvester-Bradley R (2011) Opportunities for avoidance of land-use change through substitution of soya bean meal and cereals in European livestock diets with bioethanol coproducts. *GCB Bioenergy*, **3**, 158–170.

West P, Narisma G, Barford C, Kucharik C, Foley J (2010) An alternative approach for quantifying climate regulation by ecosystems. *Frontiers in Ecology and the Environment*, **9**, 126–133.

Wicke B, Dornburg V, Junginger M, Faaij A (2008) Different palm oil production systems for energy purposes and their greenhouse gas implications. *Biomass and Bioenergy*, **32**, 1322–1337.

Wicke B, Smeets E, Tabeau A, Hilbert J, Faaij A (2009) Macroeconomic impacts of bioenergy production on surplus agricultural land—A case study of Argentina. *Renewable and Sustainable Energy Reviews*, **13**, 2463–2473.

Wicke B, Smeets E, Dornburg V, Vashev B, Gaiser T, Turkenburg W, Faaij A (2011a) The global technical and economic potential of bioenergy from salt-affected soils. *Energy & Environmental Science*, **4**, 2669–2681.

Wicke B, Smeets E, Watson H, Faaij A (2011b) The current bioenergy production potential of semi-arid and arid regions in sub-Saharan Africa. *Biomass and Bioenergy*, **35**, 2773–2786.

Wicke B, Verweij P, Van Meijl H, Van Vuuren D, Faaij A (2012) Indirect land use change: review of existing models and strategies for mitigation. *Biofuels*, **3**, 87–100.

Wicke B, Smeets E, Akanda R, Stille L, Singh R, Awan A, Faaij A (2013) Biomass production in agroforestry and forestry systems on salt-affected soils in South Asia: exploration of the GHG balance and economic performance of three case studies. *Journal of Environmental Management*, **127**, 324–334.

Wilkinson J, Herrera S (2010) Biofuels in Brazil: debates and impacts. *Journal of Peasant Studies*, **37**, 749–768.

Wirsenius S, Azar C, Berndes G (2010) How much land is needed for global food production under scenarios of dietary changes and livestock productivity increases in 2030? *Agricultural Systems*, **103**, 621–638.

Wise M, Calvin K, Thomson A, Clarke L, Bond-Lamberty B, Sands R, Edmonds J (2009) Implications of limiting CO_2 concentrations for land use and energy. *Science*, **324**, 1183–1186.

Wiskerke W, Dornburg V, Rubanza C, Malimbwi R, Faaij A (2010) Cost/benefit analysis of biomass energy supply options for rural smallholders in the semi-arid eastern part of Shinyanga Region in Tanzania. *Renewable and Sustainable Energy Reviews*, **14**, 148–165.

Woods M, Capicotto P, Haslbeck J, Kuehn N, Matuszewski M, Pinkerton L, Vaysman V (2007) *Cost and Performance Baseline for Fossil Energy Plants. Volume 1: Bituminous Coal and Natural Gas to Electricity Final Report*. National Energy Technology Laboratory, U.S. Department of Energy.

Wu C, Lin L (2009) Guest editorial. *Biotechnology Advances*, **27**, 541.

Ximenes F, George B, Cowie A, Williams J, Kelly G (2012) Greenhouse gas balance of native forests in New South Wales, Australia. *Forests*, **3**, 653–683.

Yang Y, Bae J, Kim J, Suh S (2012) Replacing gasoline with corn ethanol results in significant environmental problem-shifting. *Environmental Science and Technology*, **46**, 3671–3678.

Yoon J, Zhao L, Shanks J (2013) Metabolic engineering with plants for a sustainable biobased economy. *Annual Review of Chemical and Biomolecular Engineering*, **4**, 211–237.

Zanchi G, Pena N, Bird N (2011). Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel. *GCB Bioenergy*, **4**, 761–772.

Zhang Y, Yu Y, Li T, Zou B (2011) Analyzing Chinese consumers' perception for biofuels implementation: the private vehicles owner's investigating in Nanjing. *Renewable and Sustainable Energy Reviews*, **15**, 2299–2309.

Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1. Attributional LCA.