The economic potential of bioenergy for climate change mitigation with special attention given to implications for the land system

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Abstract

Biomass from cellulosic bioenergy crops is expected to play a substantial role in future energy systems, especially if climate policy aims at stabilizing greenhouse gas concentration at low levels. However, the potential of bioenergy for climate change mitigation remains unclear due to large uncertainties about future agricultural yield improvements and land availability for biomass plantations.

This letter, by applying a modelling framework with detailed economic representation of the land and energy sector, explores the cost-effective contribution of bioenergy to a low-carbon transition, paying special attention to implications for the land system. In this modelling framework, bioenergy competes directly with other energy technology options on the basis of costs, including implicit costs due to biophysical constraints on land and water availability.

As a result, we find that bioenergy from specialized grassy and woody bioenergy crops, such as *Miscanthus* or poplar, can contribute approximately 100 EJ in 2055 and up to 300 EJ of primary energy in 2095. Protecting natural forests decreases biomass availability for energy production in the medium, but not in the long run. Reducing the land available for agricultural use can partially be compensated for by means of higher rates of technological change in agriculture. In addition, our trade-off analysis indicates that forest protection combined with large-scale cultivation of dedicated bioenergy is likely to affect bioenergy potentials, but also to increase global food prices and increase water scarcity. Therefore, integrated policies for energy, land use and water management are needed.

Keywords: bioenergy, climate change mitigation, forest conservation, food security, biodiversity, water security

S Online supplementary data available from stacks.iop.org/ERL/6/034017/mmedia

1. Introduction

In the past, burning fossil fuels, deforestation and other human activities have released large amounts of greenhouse gases into the atmosphere. Ambitious climate protection, including a large-scale transformation of the global energy system, is needed to prevent risks to ecosystems and human societies. Over the last few years, bioenergy has gained worldwide interest for its potential to supply energy services at low levels of greenhouse gas (GHG) emissions, but also to meet rural development goals [1]. Today, almost all of the commercially available biofuels are produced from either starch- or sugar-rich crops (for bioethanol), or oilseeds (for biodiesel). Recent research has found that these bioenergy sources have their drawbacks [2, 3] and turned to the use of ligno-cellulosic feedstocks, such as perennial grasses and short rotation woody crops for bioenergy production (e.g. [4, 5]). A special point of interest is that scenarios striving for low GHG concentration targets may require options within the energy sector to remove CO_2 from the atmosphere ('negative emissions'). This implies that human-induced uptake of CO_2 would have to be larger than the amount of human-induced GHG emissions. One of the few technologies that may result in negative emissions is the combination of bioenergy and carbon capture and storage (CCS) [6].

Recent estimates on the potential global ligno-cellulosic bioenergy supply range from less than 100 EJ yr^{-1} to over 1000 EJ yr^{-1} for 2050 [7–9]. But besides biomass availability, future application of biomass for energy production is also determined by its interaction with other energy options and relative costs. In most energy scenarios, bioenergy use is projected to be in the order of 150–400 EJ in the year 2100 (e.g. [10]). Although these studies give first insights into future use of bioenergy, for assessing the potential contribution of bioenergy to the future energy mix it is indispensable to investigate the supply and demand side of bioenergy in interaction. Furthermore, claims to the land system in terms of future yield improvements and land use expansion remain unclear.

Besides uncertainties of cost-effective use of bioenergy application, large-scale energy crop production may create conflicts with other sustainability aspects, like food and water security or protection of forests for climate change mitigation and biodiversity conservation. First, bioenergy expansion is expected to put pressure on food and feed prices and costs of agricultural production [11]. Second, large-scale bioenergy production and associated additional demand for irrigation may further intensify existing pressures on water resources [12]. Third, in tropical and sub-tropical developing countries deforestation happens due to land clearing for new crop- and pasture land but also due to the use of biomass for traditional heat and energy production. There would be an additional pressure to convert forest into cropland following the large-scale cultivation of second-generation, ligno-cellulosic bioenergy crops. Forests are a major storage of carbon [13], so there is an adverse impact when forest carbon is released for the purpose of bioenergy production [14]. But deforestation not only removes a carbon sink, it is also regarded as the greatest threat to terrestrial biodiversity as forests are the most biologically diverse terrestrial ecosystems [15, 16]. Therefore, nature conservationists support forest conservation for climate change mitigation [17, 18].

The main objective of this study is to investigate the potential contribution of bioenergy to climate change mitigation, including its costs and trade-offs with food and water security in an integrated framework. In addition, we aim to assess the impacts of forest conservation on bioenergy potentials based on the rationale that bioenergy is not carbon neutral. For this, we have linked a global dynamic vegetation and water balance model, a global land and water use model, and a global energy–economy–climate model. The vegetation model supplies spatially explicit (0.5° resolution) agricultural yields and water fluxes. The land use model delivers cost-optimized land use patterns and rates of future yield increases in agricultural production. Moreover, shadow prices are calculated for irrigation water (as an indicator for water scarcity), food commodities, and bioenergy (as an indicator for changes in production costs) under different land use constraints such as forest conservation for climate change mitigation and as a contribution to biodiversity conservation. The energy–economy–climate model generates the demand for bioenergy, taking into account the direct competition with other energy technology options for GHG mitigation, based on economic costs of bioenergy production.

2. Methodology

The three models used here are the global vegetation and hydrology model LPJmL [19, 20], the global land use optimization model MAgPIE [21, 22], and the global energy–economy–climate model ReMIND [23]. A brief description of each model follows, but a more detailed discussion can be found in the supporting information (SI) (available at stacks. iop.org/ERL/6/034017/mmedia).

2.1. Model descriptions

LPJmL simulates biophysical, biogeochemical and hydrological processes on the land surface on a global 0.5° × 0.5° grid. Each grid cell considers the fractional areas of both natural ecosystems (nine plant functional types, whose geographical distribution is simulated by the model) and agricultural systems (twelve crop functional types representing the world's major crops and grazing land, whose distribution is prescribed from external data sources). In addition to food and feed crops, LPJmL also explicitly accounts for three types of specialized grassy and woody bioenergy crops, i.e. *Miscanthus*, poplar and eucalyptus, for bioenergy supply [24]. LPJmL simulates, at a daily time step, carbon fluxes (gross primary production, auto- and heterotrophic respiration) and pools (in leaves, sapwood, heartwood, storage organs, roots, litter and soil) as well as water fluxes (interception, evaporation, transpiration, soil moisture, snowmelt, runoff, discharge), in coupling with the dynamics of the vegetation. For example, carbon and water fluxes are directly linked to vegetation patterns and dynamics through the linkage of transpiration, photosynthesis and plant

water stress. Water requirements and water consumption of irrigated and rainfed crops are distinguished. The phenology (sowing and harvest dates) of the different CFTs is simulated dynamically based on CFT-specific parameters, monthly precipitation and temperature averaged over 20 years (representing farmers' past climate experience) and daily soil moisture.

MAgPIE is a mathematical programming model covering the most important agricultural crop and livestock production types in 10 economic regions worldwide (AFR = Sub-Saharan Africa, CPA = Centrally Planned Asia including China, EUR = Europe including Turkey, FSU = the Newly Independent States of the Former Soviet Union, LAM = Latin America, MEA = Middle East/North Africa, NAM = North America, PAO = Pacific OECD including Japan, Australia, New Zealand, PAS = Pacific (or Southeast) Asia, SAS = South Asia including India). It takes regional economic conditions, such as demand for agricultural commodities, economic development, and production costs as well as spatially explicit data on attainable crop yields, land and water constraints of all terrestrial grid cells from LPJmL into account and derives specific land use patterns for each grid cell (resolution of $0.5° \times 0.5°$). Moreover, the model can endogenously decide to acquire yield-increasing technological change at additional costs. The use of technological change is either triggered by a better cost-effectiveness of technological change compared to other investments or as an answer to production constraints such as land scarcity. The non-linear objective function of the land use model is to minimize the total cost of production for a given amount of regional food and bioenergy demand. Regional food energy demand is defined for an exogenously given population that changes over time in 10 food categories, based on regional diets [25]. Future trends in food demand are computed as a function of income (measured in terms of gross domestic product (GDP)) per capita based on a cross-country regression (Popp *et al* 2010). Food and feed for the 10 demand categories can be produced by 20 cropping activities and 3 livestock activities. Feed for livestock is produced as a mixture of grain, green fodder produced on crop land, and pasture. As we focus on cellulosic bioenergy crops, in this study bioenergy is supplied from specialized grassy and woody bioenergy crops, i.e. *Miscanthus*, poplar and eucalyptus. All bioenergy products in the model are delivered into an aggregated demand pool. The model computes a shadow price for binding constraints in specific grid cells, e.g. related to water availability, reflecting the amount a land manager would be willing to pay for relaxing the constraint by one unit. Furthermore, since the model minimizes production costs for a given demand for food and bioenergy products, the shadow prices for a given demand level show the marginal increase in production costs for an additional unit of output.

ReMIND is an integrated modelling framework that embeds a detailed energy system model (ESM) within a macro-economic intertemporal growth model with perfect foresight and a climate system model that computes the effect of GHG emissions on global mean temperature (GMT). The present study uses a global single-region version. The energy sector comprises a large number of energy conversion technologies
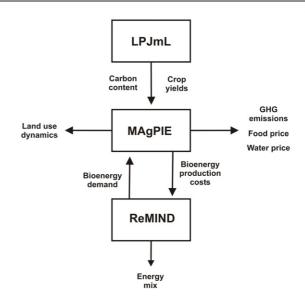

Figure 1. Information flow within the modelling framework. In a pre-processing step, the land use model MAgPIE is informed by data on crop yields and carbon content from the biophysical model LPJmL. The energy–economy–climate model ReMIND and the MAgPIE model are coupled by exchanging price and quantity information on bioenergy.

that convert primary energy carriers into final energy carriers that are supplied to the macro-economic framework. Given various economic, technological and natural constraints, the optimal solution implies an efficient allocation of investments into energy conversion technologies and macro-economic capital accumulation. In the case of climate change mitigation, an energy mix is chosen that reduces GHG emissions and minimizes mitigation costs. Ligno-cellulosic biomass is a primary energy carrier that can be converted into various types of final energy: most notably the ReMIND model comprises combined heat and power plants, heat plants, synthetic natural gas, solid biomass, hydrogen and Fischer–Tropsch plants. If biomass is combined with carbon capture and sequestration, net emissions can be negative.

2.2. Coupling

Figure 1 gives an overview on how the model components interact.

First, LPJmL-simulated, spatially explicit attainable production levels of food, feed and bioenergy crops under explicit consideration of water limitation are provided to the MAgPIE model at a 0.5° resolution. Then, MAgPIE simulates spatially explicit land use and irrigation water use patterns, while at the same time taking effects of technological and agro-economic change into account. This flexibly integrates biophysical constraints into an economic decision-making model and provides a straightforward link between monetary and physical processes.

Second, the ReMIND and the MAgPIE models are coupled by exchanging price and demand information on bioenergy. However, the exchange of price and demand information is limited in terms of computational efficiency
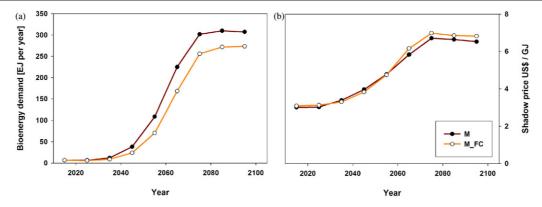
Figure 2. Bioenergy demand and prices (time series until 2095) for the scenario with bioenergy for climate change mitigation (M) (red line) and the scenario with bioenergy and avoided deforestation for climate change mitigation (M_FC) (orange line).

and solvability because both models are applying optimization methods. Therefore, we use a soft-linked approach [26] where both models are solved in isolation and information flows between them are brought into agreement in an iterative process (meta-optimization).

The chain starts with ReMIND (R) calculating a global bioenergy demand scenario (B) in the energy system up to 2100 based on given biomass cost curves (S_B).

$$B = R(S_B). \qquad (1)$$

This data is delivered to MAgPIE (M) for computing new cost curves for biomass for the biomass scenario obtained from ReMIND.

$$S_B = M(B) \qquad (2)$$

Since MAgPIE minimizes production costs for a given demand for bioenergy products, these numbers show the marginal increase in production costs for an additional unit of output. This can also be interpreted as the minimum price that the energy sector would have to pay for one additional unit of bioenergy from the agricultural sector. If e.g. prices for mineral oil would increase, e.g. due to shrinking reserves or effects of emission regulations, this would translate into a higher demand for bioenergy, which would in turn raise the shadow price for bioenergy in our model. The shadow price of the global demand constraint in the model reflects the changes in the aggregate world market price for bioenergy feedstocks.

Global bioenergy demand from ReMIND is fulfilled by MAgPIE without any trade restrictions, i.e. biomass will be produced globally according to regional comparative advantages (in areas with most suitable production conditions and, hence, lowest costs of production). As an economic optimization model, MAgPIE delivers spatially explicit land use patterns and converts explicit restrictions on land and water availability into implicit costs of bioenergy production to be used in the energy system model. This iterative process is repeated until equilibrium is established, i.e. no more changes in bioenergy demand (derived by ReMIND) and costs (derived by MAgPIE) occur.

2.3. Scenarios

We apply our land use energy–economy–climate modelling framework under different land use scenarios to assess the potential contribution of bioenergy to climate change mitigation, including its costs and side effects. A 'reference scenario' (Ref) portrays a possible future with growing population, increasing food and feed demand, but without bioenergy demand for climate change mitigation and with all suitable land available for cropland expansion. Suitable land is defined by the Global Agro-Ecological Zone (GAEZ) methodology using the land suitability index [27, 28]. In our approach, productive land has to be at least marginally suitable for rainfed crop production according to climate parameters, topography and soil type, and is not covered by built-up, grazing or forestry land. This scenario serves as a point of reference for the assessment of technological change in agricultural production (i.e. yield increase), land use dynamics and shadow prices for food and irrigation water. In the climate change mitigation scenario (M), bioenergy demand is calculated by ReMIND under climate policies that limit GHG emissions in the energy sector until 2095–1100 Gt CO_2 with the aim to stay below 2 °C change in global mean temperature (GMT), compared to the pre-industrial level. But especially in tropical and sub-tropical developing countries, bioenergy production is expected to increase the conversion of intact and frontier forests into cropland. These forests represent areas of high value for carbon [29] and for biodiversity [16], so there is a potentially adverse impact when forest carbon is released for the purpose of bioenergy production [30, 31]. Therefore, in the forest conservation scenario (M_FC) we additionally constrain the land pool available for cropland expansion by excluding the share of presently intact and frontier forests [32, 33] for each grid cell. By this approach, the amount of suitable land for cropland expansion is reduced by 74% globally.

3. Results

3.1. Cost-effective contribution of bioenergy

In the scenario without forest conservation (M), bioenergy demand increases up to about 300 EJ in 2095 with a demand of about 100 EJ in 2055 (figure 2(a)). This demand scenario
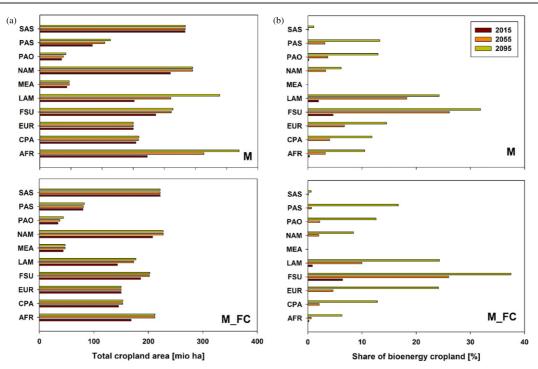
Figure 3. Total agricultural land (a) and share of bioenergy cropland in total cropland (b) for the scenario with bioenergy for climate change mitigation (M) (upper row) and the scenario with bioenergy and avoided deforestation for climate change mitigation (M_FC) (lower row) in 2015 (red bars), 2055 (orange bars) and 2095 (yellow bars).

is a result of the economic interplay between the agricultural and the energy sector where simulated bioenergy prices are rising to 7 US$ per GJ in 2095 (figure 2(b)). For this specific scenario, biomass from dedicated bioenergy crops will contribute 25% to the total global demand for primary energy carriers (figure SI3 available at stacks.iop.org/ERL/6/034017/mmedia). 95% of the bioenergy production will be converted into secondary energy in combination with carbon capture and storage (CCS). This combination of technologies enters the market between 2020 and 2030 (figure SI4 available at stacks.iop.org/ERL/6/034017/mmedia) and has the unique feature of providing 'negative emissions'. However, forest exclusion for the purpose of biodiversity conservation and climate change mitigation affects the availability of cost-efficient biomass for energy production significantly. The amount of bioenergy supplied is reduced to about 70 EJ in 2055 and 270 EJ in 2095 in the scenario with 100% forest conservation (M_FC) (figure 2(a)).

3.2. Land expansion and technological change

In the reference scenario (Ref), total cropland (excluding abandoned land) increases from 1442 million ha in 2005 to 1770 million ha in 2095. In the scenario without forest conservation (M), cultivation of dedicated bioenergy crops increases total cropland to 1830 million ha, but forest exclusion (M_FC) limits total cropland to 1520 million ha in 2095 (figure 3(a)). In the M scenario, highest increases in cropland area compared to 2005 can be observed in LAM (98%), AFR (89%) and PAS (39%). In the M_FC scenario, highest increases in total cropland area until 2095 occur in PAO (30%), AFR

(26%) and LAM (24%). Our simulation results reveal that in the scenario without forest conservation (M) up to 29 Gt of additional cumulative CO_2 emissions from land use change due to the cultivation of dedicated bioenergy crops are likely to occur until 2095. These co-emissions are negligible in the scenario with forest conservation (M_FC) (figure SI5 available at stacks.iop.org/ERL/6/034017/mmedia).

In 2095, highest shares of cropland used for bioenergy crop cultivation (figure 3(b)) can be found in FSU (31%) and LAM (24%) in the M scenario, and in FSU (37%) and LAM (23%) in the M_FC scenario.

Figure 4 indicates (i) total cropland share and (ii) bioenergy cropland share for each grid cell, as derived by MAgPIE for the mitigation scenario without forest exclusion (M) and the forest conservation scenario (M_FC) in 2095. The maps show that, the more forest is available for agricultural land expansion, the more cropland is shifted towards tropical regions where today large amounts of intact tropical forests can be found, especially in AFR, LAM and PAS.

The second mechanism that allows increasing food and bioenergy production is through intensification and technological change on currently used agricultural land. In the 'reference scenario' (Ref), an average global rate of yield increase of 0.6% per year is projected until 2095. This is equivalent to an increase in yields by the factor 1.8 in 100 years. Due to increasing bioenergy demand the global rate of yield increase would have to rise to 0.8% per year (M). The highest rate (0.9% per year until 2095) can be found in the forest conservation scenario (M_FC), due to additional restrictions of land availability for agricultural expansion, figure 5 shows that in the M scenario, compared to the
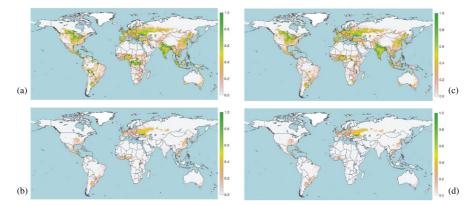
Figure 4. (a) Cell-specific share of total crop land and (b) share of bioenergy cropland in total cropland for the scenario with bioenergy (M) as well as (c) cell-specific share of total crop land and (d) share of bioenergy cropland in total cropland for the scenario with bioenergy and avoided deforestation (M_FC) (right column) in 2095.
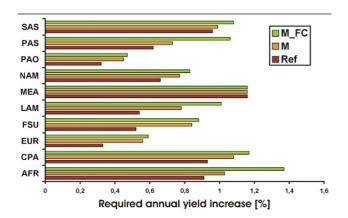

Figure 5. Required annual yield increase until 2095 for the reference scenario (Ref) (black bars), the scenario with bioenergy for climate change mitigation (M) (light grey bar) and the scenario with bioenergy and avoided deforestation for climate change mitigation (M_FC) (dark grey bar).

reference scenario (Ref), yield increases due to the enhanced cultivation of dedicated bioenergy crops rise most strongly in FSU, CPA and LAM. If, in addition, natural forests were conserved (M_FC), highest yield increases can be found in LAM, AFR and PAS.

3.3. Food and water prices

Figure 6 shows the regional aggregated food price index, i.e. the average of all crop and livestock products weighted with their average share in total food demand. Compared to Ref, the food price index rises most strongly in EUR (22%) and FSU (16%) until 2095 if climate change mitigation is taken into account and all suitable land is available for land expansion (M). But if forest conservation (M_FC) is considered, the food price index rises most prominently in AFR (82%), LAM (73%) and PAS (52%) until 2095, compared to the reference scenario.

In the scenario without forest conservation (M), strongest growth in the regional water price index, i.e. changes in shadow prices for irrigation water relative to the reference scenario until 2095, can be found in LAM (210%), FSU (170%) and
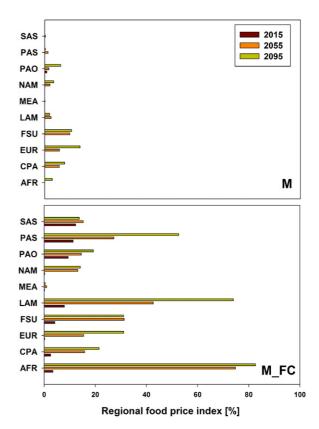

Figure 6. Regional food price index, i.e. the average of all cropping and livestock activities weighted with their share in total demand. The food price index describes relative changes to the reference scenario (no bioenergy demand for climate change mitigation and all suitable land available for cropland expansion) for each year.

PAS (130%) (figure 7). In this case, bioenergy cropland competes directly for irrigation water with other agricultural activities. The forest conservation scenario (M_FC) increases the regional water price index most heavily in LAM (460%), AFR (390%) and PAS (330%).

4. Discussion

Our study aims at assessing the cost-effective contribution of bioenergy to climate change mitigation by coupling
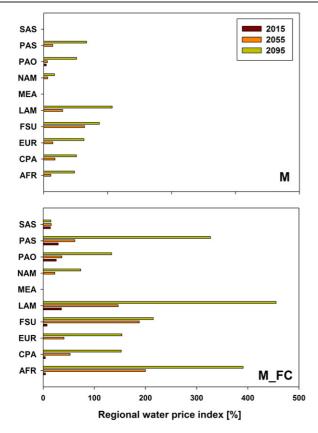
Figure 7. Regional water price index. The water price index describes changes in shadow prices for irrigation water relative to the reference scenario (no bioenergy demand for climate change mitigation and all suitable land available for cropland expansion) as a mean over all years (2015–95) for all regions.

and applying the vegetation and hydrology model LPJmL, simulating agricultural yields and hydrological processes, the land use optimization model MAgPIE, simulating the costs of biomass supply, and the energy–economy–climate model ReMIND, simulating the demand for bioenergy. Our simulation results reveal that the energy sector uses about 100 EJ globally in 2055 and up to 300 EJ in the year 2095 from dedicated energy crops, if all suitable land for agricultural production was made available for land expansion. However, cultivation of bioenergy crops has several effects: it increases crop land expansion; it takes over a huge share in total cropland; it is mainly located in areas that today are occupied by intact ecosystems; and it increases CO_2 emissions from deforestation. Thus, converting intact ecosystems, such as tropical rainforests or open woodlands, which store large amounts of carbon and belong to the most diverse terrestrial ecosystems, counteracts global climate and biodiversity protection goals [24]. For bioenergy to make a real net contribution to climate change mitigation, intact forests have to be protected (e.g. [5]). Our analysis shows that in the scenario where intact and frontier forests are excluded the reduced land pool available for agricultural use would have to be compensated by higher rates of technological change (0.9% per year until 2095) at additional costs to fulfil the demand for bioenergy. Simulated rates of technological change have to be seen in comparison with historical yield growth of about 1.3%

annually from 1970 to 1995 averaged across all crops [25]. Yield growth rates have declined in the most recent decade [34] but yield growth potential is still considerable [35].

Due to rising bioenergy prices, restrictions for land availability decrease bioenergy use in the energy system in 2055 considerably to about 70 EJ. But in the long run (until 2095) the use of biomass in the energy system is competitive, mainly due to the option of generating negative emissions in the energy system by using CCS (figure SI4 available at stacks.iop.org/ERL/6/034017/mmedia). Reason is the difficulty to supply the transportation sector with low-carbon fuels. Bioenergy is partly converted to fuels and partly to electricity, both in combination with CCS. In our model, the resulting negative emissions compensate for higher gross emissions from fossil fuels. However, with respect to the importance of CCS for the contribution of bioenergy to climate change mitigation one needs to consider that the availability of this technology is still uncertain and not yet proven on a large scale. CCS will require huge infrastructure developments, in particular a pipeline network similar to the existing gas transport infrastructure, and new storage capacities. In addition, hazards and risks related to this technology, such as leakage of stored and transported CO_2, ground instabilities or contamination of groundwater [36], are not considered in our modelling approach.

Our results are in the lower range of recent studies of bioenergy potentials. The potential supply of bioenergy production from dedicated energy crops, as reported in the literature, varies from zero to several hundreds of EJ per year (e.g. [7, 8, 24, 33, 37–39]). These ranges differ due to large discrepancies in assumptions about land availability for biomass plantations and yield levels (including future yield improvements) in crop production. For example, the highest biomass potential of 1500 EJ for 2050 [38] is based upon an extremely intensive, technologically very highly developed agriculture. On the contrary, the lowest biomass potential for 2050 [39] is based on a pessimistic scenario with high population growth, high food demands and extensive agricultural production systems. Our approach for assessing bioenergy potentials has the great advantage that, on the one hand, it considers the trade-off between land expansion and yield-increasing technological change endogenously. On the other hand, it is based on a global biogeochemical and bioclimatic analysis of plant growth potentials in contrast to assessments that have simply extrapolated findings from plantation field studies to the larger scale (such as [37]). Therefore, limitations of global biomass potential due to limitations in water availability for plant transpiration [40] have been frequently underestimated or downplayed, if not ignored [41].

The cost-effective and sustainable contribution of bioenergy from dedicated energy crops to climate change mitigation, as it has been assessed in this study, can be enhanced or reduced if other assumptions are taken into account. On the one hand, other biomass resources such as the use of agricultural and forest residues, ranging from very low estimates to around 100 EJ [7], could be considered. However, competing applications of biomass for soil improvement or animal feed

could reduce the potential of residues for bioenergy application to the lower end of the range [42]. On the other hand, our assumption on global availability of cellulosic biomass without any trade restrictions may overestimate our calculated bioenergy potentials. Even though the volume of biomass trade for food, feed and fibre has grown rapidly in recent years [43], trade of biomass for bioenergy is in its initial phases, with wood pellets, ethanol, and palm oil being typical examples to meet growing demand [44]. Transportation of cellulosic biomass for bioenergy production could become more efficient by converting biomass into charcoal and thus increasing its energy content [45].

While assessing biomass production potentials, it is important to consider the complex linkages between large-scale cultivation and use of biomass for energy and climate change mitigation, and conflicts with other sustainability aspects. First, besides co-emissions from deforestation, large-scale cultivation of perennial ligno-cellulosic bioenergy crops is expected to increase the competition for land and therefore raise N_2O emissions from agricultural soils due to intensification. Popp *et al* [46] showed that these co-emissions from bioenergy production are only a minor factor compared to the mitigation potential of bioenergy in the long run. Second, avoiding deforestation for biodiversity conservation by excluding intact forests (mainly in the tropics) from suitable land for cropland expansion could add additional pressure on other natural ecosystems with extraordinary biodiversity, such as savannas.

Other studies (e.g. [47]) indicate that systems integrating bioenergy and feed production and producing synergies do exist. To some extent, these types of innovation are implicitly considered in our additional technological change in agriculture. However, the large-scale use of biomass for bioenergy production as indicated in our study will still affect food and water security due to increased competition for land, water and other inputs of agricultural production. We have shown that food prices and the implicit values of irrigation water are only slightly affected without forest conservation, but rise significantly (especially in the tropics) if forests are excluded from available land for future cropland expansion. Higher food prices follow directly from competition with energy crops, due to limitations in land availability and associated needs for technological development at additional costs. Shadow prices of irrigation water rise with increasing forest conservation, because less land is available for rainfed agriculture, and biomass accumulation for dedicated bioenergy cultivation leads to higher evapotranspiration rates, which can reduce water availability in regions where water is already scarce [48]. This is a strong indication that the competition for water between agriculture, private households, and industry is likely to increase heavily in many regions. Furthermore, our analysis indicates that competition for water may not only increase in regions where bioenergy crops are cultivated or where forests are conserved (i.e. Latin America). To gain space for bioenergy crops and forest conservation, agricultural production of food and livestock feed is likely to be shifted to other regions (i.e. South Asia) which are originally not directly affected by these activities and thereby increase shadow prices of irrigation water there indirectly.

We conclude that bioenergy from dedicated ligno-cellulosic energy crops is likely to be a cost-efficient contribution to the future energy mix. Without considering co-emissions from deforestation, biodiversity issues, and impacts on food and water security, the biomass resource potential could deliver a considerable amount of the world's primary energy demand up to 2095. Our trade-off analysis indicates, however, that restrictions on land availability, by protecting untouched tropical forests and other high-carbon ecosystems, are likely to reduce bioenergy potentials significantly in the medium run, but less so in the long run. Most likely, forest conservation combined with large-scale cultivation of dedicated bioenergy for climate change mitigation will generate conflicts with respect to food supply and water resource management. Integrated policies for energy production, land use and water management are therefore needed to steer the potential contribution of bioenergy to the future energy mix, without neglecting the side effects on land-use-related GHG emissions, biodiversity conservation, food and water security.

Acknowledgments

References

[1] McLaughlin S B, de la Torre Ugarte D G, Garten C T Jr, Lynd L R, Sanderson M A, Tolbert V R and Wolf D D 2002 *Environ. Sci. Technol.* **36** 2122–9

[2] Crutzen P J *et al* 2007 N_2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels *Atmos. Chem. Phys. Discuss.* **7** 11191–205

[3] Searchinger T, Heimlich R, Houghton R A, Dong F, Elobeid A, Fabiosa J, Tokgoz S, Hayes D and Tun-Hsiang Yu 2008 Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change *Science* **319** 1238–42

[4] Schmer M R, Vogel K P, Mitchell R B and Perrin R K 2008 Net energy of cellulosic ethanol from switchgrass *Proc. Natl Acad. Sci. USA* **105** 464–9

[5] Melillo J M *et al* 2009 Indirect emissions from biofuels: how important? *Science* **326** 1397–9

[6] Haszeldine R S 2009 Carbon capture and storage: how green can black be? *Science* **325** 1647–52

[7] Berndes G, Hoogwijk M and van den Broek R 2003 The contribution of biomass in the future global energy supply: a review of 17 studies *Biomass Bioenergy* **25** 1–28

[8] Dornburg V *et al* 2010 Bioenergy revisited key factors in global potentials of bioenergy *Energy Environ. Sci.* **3** 258–67

[9] Haberl H, Beringer T, Bhattacharya S C, Erb K-H and Hoogwijk M 2010 The global technical potential of

bio-energy in 2050 considering sustainability constraints *Curr. Opin. Environ. Sustain.* **2** 394–403

[10] Edenhofer O *et al* 2010 The economics of low stabilisation exploring its implications for mitigation costs and strategies *Energy J.* **31** 11–48

[11] Goldemberg J 2007 Ethanol for a sustainable energy future *Science* **315** 808–10

[12] Fingerman K, Torn M, O'Hare M and Kammen D 2010 Accounting for the water impacts of ethanol production *Environ. Res. Lett.* **5** 014020

[13] Gumpenberger M, Vohland K, Heyder U, Poulter B, Macey K, Rammig A, Popp A and Cramer W 2010 Predicting pan-tropical climate change induced forest stock gains and losses—implications for REDD *Environ. Res. Lett.* **5** 014013

[14] Fargione J, Hill J, Tilman D, Polasky S and Hawthorne P 2008 Land clearing and the biofuel carbon debt *Science* **319** 1235–8

[15] Turner I M 1996 Species loss in fragments of tropical rain forest a review of the evidence *J. Appl. Ecol.* **33** 200–9

[16] Hassan R, Scholes R and Ash N (ed) 2005 Ecosystems and Human Well-Being: Current State and Trends *Findings of the Condition and Trends Working Group* (Washington, DC: Island Press) pp 77–122

[17] Laurance W F 2007 Have we overstated the tropical biodiversity crisis? *Trends Ecol. Evol.* **22** 65–70

[18] Barlow J *et al* 2007 Quantifying the biodiversity value of tropical primary, secondary and plantation forests *Proc. Natl Acad. Sci. USA* **104** 18555–60

[19] Bondeau A *et al* 2007 Modelling the role of agriculture for the 20th century global terrestrial carbon balance *Glob. Change Biol.* **133** 679–706

[20] Rost S, Gerten D, Bondeau A, Lucht W, Rohwer J and Schaphoff S 2008 Agricultural green and blue water consumption and its influence on the global water system *Water Resour. Res.* **44** W09405

[21] Lotze-Campen H, Müller C, Bondeau A, Jachner A, Popp A and Lucht W 2008 Global food demand, productivity growth, and the scarcity of land and water resources: a spatially explicit mathematical programming approach *Agricult. Econ.* **39** 325–38

[22] Popp A, Lotze-Campen H and Bodirsky B 2010 Food consumption, diet shifts and associated non-CO_2 greenhouse gas emissions from agricultural production *Glob. Environ. Change* **20** 451–62

[23] Leimbach M, Bauer N, Baumstark L and Edenhofer O 2009 Costs in a globalized world climate policy analysis with REMIND-R *Environ. Model. Assess.* **15** 155–73

[24] Beringer T, Lucht W and Schaphoff S 2011 Bioenergy production potential of global biomass plantations under environmental and agricultural constraints *Glob. Change Biol. Bioenergy* **3** 299–312

[25] FAOSTAT 2008 www.faostat.fao.org (last accessed 8 November 2008)

[26] Bauer N, Edenhofer O and Kypreos S 2008 Linking energy system and macroeconomic growth models *CMS* **5** 95–117

[27] Velthuizen H *et al* 2007 *Mapping Biophysical Factors that Influence Agricultural Production and Rural Vulnerability* (*Environment and Natural Resources* Series 11) (Rome: FAO)

[28] Fischer G, Shah M, van Velthuizen H, Medow S and Nachtergaele F O 2002 *Global Agroecological Assessment for Agriculture in the 21st Century* (International Institute for Applied Systems Analysis (IIASA) and FAO) (www.iiasa.ac.at/Research/LUC/SAEZ/index.html)

[29] Houghton R A 2003 Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850–2000 *Tellus* B **55** 378–90

[30] Wise M, Calvin K, Thomson A, Clarke L, Bond-Lamberty B, Sands R, Smith S, Janetos A and Edmonds J 2009 Implications of limiting CO_2 concentrations for land use and energy *Science* **324** 1183–6

[31] Persson U M and Azar C 2010 Preserving the World's Tropical Forests—a price on carbon may not do *Environ. Sci. Technol.* **44** 210–5

[32] Bryant D, Nielsen D and Tangley L 1997 *The Last Frontier Forests—Ecosystems & Economies on the Edge* (Washington, DC: World Resources Institute (WRI))

[33] van Vuuren D P, Van Vliet J and Stehfest E 2009 Future bio-energy potential under different assumptions *Energy Policy* **37** 4220–30

[34] Fischer R A and Edmeades G O 2010 Breeding and cereal yield progess *Crop Sci.* **50** 85–9

[35] Licker R, Johnston M, Foley J A, Barford C, Kucharik C, Monfreda C and Ramankutty N 2010 Mind the gap: How do climate and agricultural management explain the 'yield gap' of croplands around the world? *Global Ecol. Biogeogr.* **19** 769–82

[36] Field C B, Campbell J E and Lobell D B 2008 Biomass energy: the scale of the potential resource *Trends Ecol. Evol.* **23** 65–72

[37] Knopf B, Edenhofer O, Flachsland C, Kok M T J, Lotze-Campen H, Luderer G, Popp A and van Vuuren D P 2010 Managing the low-carbon transition—from model results to policies *Energy J.* **31** (Special Issue 1) 223–45

[38] Smeets E M W, Faaij A P C, Lewandowski I M and Turkenburg W C 2007 A bottom-up assessment and review of global bio-energy potentials to 2050 *Prog. Energy Combust. Sci.* **33** 56–106

[39] Wolf J, Bindraban P S, Luijten J C and Vleeshouwers L M 2003 Exploratory study on the land area required for global food supply and the potential global production of bioenergy *Agricult. Syst.* **76** 841–61

[40] Rost S, Gerten D, Hoff H, Lucht W, Falkenmark M and Rockström J 2009 Global potential to increase crop production through water management in rainfed agriculture *Environ. Res. Lett.* **4** 044002

[41] Berndes G 2002 Bioenergy and water—the implications of large-scale bioenergy production for water use and supply *Glob. Environ. Change* **12** 253–71

[42] Lal R 2005 World crop residues production and implications of its use as a biofuel *Environ. Int.* **31** 575–84

[43] Erb K, Krausmann F, Lucht W and Haberl H 2009 Embodied HANPP mapping the spatial disconnect between global biomass production and consumption *Ecol. Econom.* **692** 328–34

[44] Heinimö J and Junginger M 2009 Production and trading of biomass for energy—an overview of the global status *Biomass Bioenergy* **33** 1310–20

[45] Hilring B 2006 World trade in forest products and wood fuel *Biomass Bioenergy* **30** 315–25

[46] Popp A, Lotze-Campen H, Leimbach M, Knopf B, Beringer T, Bauer N and Bodirsky B 2011 On sustainability of bio-energy production: integrating co-emissions from agricultural intensification *Biomass Bioenergy* at press (doi:10.1016/j.biombioe.2010.06.014)

[47] Dale B E, Bals B D, Kim S and Eranki P 2010 Biofuels done right: land efficient animal feeds enable large environmental and energy benefits *Environ. Sci. Technol.* **44** 8385–9

[48] Jackson R B, Jobbágy E G, Avissar R, Roy S B, Barrett D J, Cook C W, Farley K A, le Maitre D C, McCarl B A and Murray B C 2005 Trading water for carbon with biological carbon sequestration *Science* **310** 1944–7