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OPINION

Economic and ecological views on climate change mitigation with bioenergy and negative emissions

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Abstract

Climate stabilization scenarios emphasize the importance of land-based mitigation to achieve ambitious mitigation goals. The stabilization scenarios informing the recent IPCC's Fifth Assessment Report suggest that bioenergy could contribute anywhere between 10 and 245 EJ to climate change mitigation in 2100. High deployment of bioenergy with low life cycle GHG emissions would enable ambitious climate stabilization futures and reduce demands on other sectors and options. Bioenergy with carbon capture and storage (BECCS) would even enable so-called negative emissions, possibly in the order of magnitude of 50% of today's annual gross emissions. Here, I discuss key assumptions that differ between economic and ecological perspectives. I find that high future yield assumptions, plausible in stabilization scenarios, look less realistic when evaluated in biophysical metrics. Yield assumptions also determine the magnitude of counterfactual land carbon stock development and partially determine the potential of BECCS. High fertilizer input required for high yields would likely hasten ecosystem degradation. I conclude that land-based mitigation strategies remain highly speculative; a constant iteration between synoptic integrated assessment models and more particularistic and fine-grained approaches is a crucial precondition for capturing complex dynamics and biophysical constraints that are essential for comprehensive assessments.

Keywords: BECCS, bioenergy, biophysical limits, climate change, life cycle emissions, risks, yields

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Introduction

The recent IPCC assessment established a comprehensive picture on bioenergy (Creutzig *et al.*, 2014; Smith *et al.*, 2014). It is clear that great uncertainty surrounds the key questions of sustainable potential and mitigation effects. Importantly, different communities approach this topic with a different vocabulary and – while broadly consistent – emphasize different conclusions.

Climate stabilization scenarios, and in particular integrated assessment models (IAMs), explore the long-term solution space for climate change mitigation. They constitute the backbone of IPCC mitigation reports. Due to the complexity of the underlying bio-geophysical and socioeconomic systems, recent studies have called for increasing interaction between physical, biological, and social scientists for creating the next generation of IAMs in general (Moss *et al.*, 2010) and for bioenergy specifically (Creutzig *et al.*, 2012a,b; Meller *et al.*, 2013). This perspective looks at a particular but crucial subset of assumptions in IAMs that study future bioenergy deployment: yields and effects on global warming, as part of an economically constrained model. It then compares these assumptions with findings of ecologically minded studies, which emphasize biological and/or physical factors (e.g., Haberl *et al.*, 2013a). IAMs broadly capture many important findings from ecological studies. But the latter suggest that IAMs could sample more densely a certain part of the assumption space to more comprehensively reflect the findings from fine-grained studies. The different choices in emphasis may be grounded in varying explicit or implicit objective functions and have considerable implications for assessments.

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Technical potential

How much bioenergy can be supplied? Several analyses have tried to estimate the sustainable technical potential of bioenergy. Reviewing eight studies on the technical potential of bioenergy in 2050, Dornburg *et al.* (2010) consider food, water, and biodiversity constraints, focusing mostly on studies from integrated assessments and economic estimates; they find a technical sustainable potential between 200 and 500 EJ yr^{-1}. Creutzig *et al.* (2014) find that about 100 EJ from different sources could be deployed sustainable, and possibly much more (up to 900 EJ), but at steadily increasing risks to sustainability. Haberl *et al.* (2010) estimate a sustainable technical potential of energy crops in 2050, reviewing three detailed studies, based on three different methods that consider environmental targets. The estimated potential for energy crops is 81 EJ yr^{-1}, with a range from 44 to 133 EJ yr^{-1} [for a similar result see (Schüler *et al.*, 2013)]. Together with residues from forestry and agriculture, this amounts to a total sustainable technical potential of 160–270 EJ yr^{-1}. In contrast to the technical potential, IAMs estimate economic potentials: how much bioenergy could cost-efficiently be produced in climate change mitigation scenarios. IAM studies, in general, display a range of uncertainty, projecting between 20 and 300 EJ yr^{-1} bioenergy actual deployment in 2100 (Fischedick *et al.*, 2011). In these assessment models, bioenergy deployment is driven by climate change mitigation, indicating higher deployment for more ambitious mitigation targets. The upper range (>200 EJ) of what is suggested to be economically plausible and contributing to climate change mitigation is contested both in feasibility and normative desirability. Where one community sees chances, the other sees risks. It is hence important to understand the divergent intuitions of different communities.

The IAM perspective

Several options would enable future bioenergy deployment beyond 200 EJ. First, high yields of energy crops would imply low land demand. Second, high yield growth in food crops would free land for bioenergy. Third, land currently unused could be utilized for bioenergy. And forth, energy crops could substitute for other existing land use.

Integrated assessment models make use of these options in modeling potentially high bioenergy yields. Several examples illustrate these options. Edmonds *et al.* (2013) judge 300 EJ yr^{-1} as feasible, pointing to a carbon-price-induced diet shift away from meat to a vegetarian diet, which would provide another 250 Mha for bioenergy. Kriegler *et al.* (2013) assume that bioenergy supply of 200 EJ yr^{-1} can be obtained from abandoned land, referring to IPCC scenario A1 in figure 7 (Chapter 4) on p. 103 of Hoogwijk (2004). figure 7 (Chapter 3) of Hoogwijk (2004) shows that this 'abandoned' land is currently agricultural land in use, which is modeled to get abandoned between 2000 and 2050 by increases in agricultural productivity. In Hoogwijk (2004; see also Hoogwijk *et al.* (2005)), the 1300 Mha area of available abandoned agricultural land in 2050 are obtained from a transformation of currently productive agricultural land from 1998 until 2050 (the total agricultural land for food production is reduced by approximately 50%). This is possible by an assumed high increase in agricultural productivity of about a factor of 2 and with bioenergy produced at in average about 40 t dry biomass ha^{-1} yr^{-1}. A review of IAM models finds that future bioenergy yields are assumed to hover between 8 and 26 t ha^{-1} yr^{-1} (or 160–490 GJ primary energy yr^{-1}) (Popp *et al.*, 2014).

Clearly then, high yields are more often than not the most important modeling component in IAMs enabling high bioenergy deployment. It is hence important to investigate the plausibility of these yields assumptions. And indeed, such high yields are possible, in principle. Field trials have demonstrated yield potentials of bamboo and miscanthus of about 3–50 t ha^{-1} yr^{-1}, depending on nitrogen, water, temperature, and plant density (Hong *et al.*, 2011). Other sources identify field trials with 30 t ha^{-1} yr^{-1} in Southern Europe for irrigated miscanthus and 10–25 t ha^{-1} yr^{-1} for nonirrigated miscanthus (Lewandowski *et al.*, 2000). More generally, the potential biofuels from miscanthus, switchgrass, and sugarcane are exceeding that of corn ethanol by a factor of 2–3 if agronomy and genetics are improved (Heaton *et al.*, 2008). Climate change also offers positive feedbacks on yields: Higher atmospheric CO_2 concentration induces CO_2 fertilization, specifically of C3 plants, that is argued to increase yields (e.g., CO_2 fertilization effect seems to be relevant in Van Vuuren *et al.* (2011)). Hence, the assumptions of about 8–26 t ha^{-1} yr^{-1} reported in IAMs can be justified. IAMs point to a consistent carbon price for both biospheric and fossil carbon as a precondition to fully realize these potentials. Under this condition, and with additional land demand for other purposes such as food production, the value of land would increase rapidly and globally and market forces would foster high yield growth. How does the ecological perspective contrast these assumptions?

The ecological perspective

Researchers coming from an ecological perspective argue roughly as follows. Currently, bioenergy from biomass consumes about two order of magnitudes more land than solar and wind energy per unit primary energy (Dijkman & Benders, 2010). This high land intensity requires an estimation of the amount of land available that leaves the biosphere largely intact. Humans appropriate currently around 30% of the net primary aboveground productivity (NPP: the net amount of carbon assimilated in a given period by vegetation), which translates into around 300 EJ yr^{-1} of gross primary energy used for human purposes, notably food, but including traditional bioenergy (Haberl *et al.*, 2007). This amount of human impact leads already to unprecedented biodiversity loss (Haberl *et al.*, 2013a). The fear is that considerable deployment of bioenergy would escalate this situation. A second argument is that the NPP without human interference serves as a benchmark for productivity (Field *et al.*, 2008). For example, the agricultural systems have on average around 35% less NPP compared to native vegetation on the same lands (Field *et al.*, 2008). Starting from this position, Field *et al.* (2008) suggest that about 0.4 Gha area of abandoned land would be available in 2050, which has a net primary production of around 3.2 tC ha^{-1} yr^{-1}, about 1/5 of highly productive tropical forests (DeLucia *et al.*, 1999). These estimates result in 27 EJ yr^{-1} that could be harvested from abandoned land without interfering with food security. That study also has a conservative understanding of the possibilities of technological change. In contrast, the review of Haberl *et al.*, 2010 mentioned above allows for 2–3 times higher yield technically attainable than estimated in Field *et al.*, 2008.

A decisive question is how close real world yields can get to technically possible yields (see on this also fig. 5 in Smith *et al.* (2012)). Average worldwide yield in commercial production is consistently far below maximally observed yields (Thomson *et al.*, 2009) for the case of switchgrass. Corn yields are in average worldwide below 5 t ha^{-1} yr^{-1} (Bruinsma, 2009), while specific parts of world exceed that average by a factor of 2.3 (e.g., DeWitte, 2009), and highest yield fields exceed that average by a factor of 4.5 (Elmore & Abendroth, 2013). These high yields, tuned for winning competitions, may require uneconomically high water and management input (Elmore & Abendroth, 2013) and are not mirrored in average yield increases (Duvick & Cassman, 1999). Evidence also suggests that yields grow linearly, not exponentially (Fargione *et al.*, 2010). The FAO assumes an agricultural productivity increase of 1.63 and projects an increase of agricultural land for food production by 70 Mha from 2005 to 2050 (Bruinsma, 2009) needed to feed 9 billion people. In that case, no land would be freed up for bioenergy. Haberl *et al.* point to three other factors that potentially could lead to a downgrading future deployment: (1) Negative climate effects are likely to outweigh positive climate effects [heat events have reduced yield growth rate by about 10% from 1980 onwards (Lobell *et al.*, 2011)], and the CO_2 fertilization effect is highly uncertain, with reduced tree longevity offsetting the effect (Bugmann & Bigler, 2011) and with water and nitrogen availability constraining its magnitude (Reich *et al.*, 2014); (2) biomass plantations could compete with food for water resources, and other food-energy market interactions; and (3) removing residues could have a negative effect on soil carbon and reduce fertility. Hence, in total, this ecological side of the literature suggests that high-yield scenarios in IAMs are mostly unrealistic.

Implications for the carbon balance

Yield expectations have important implications on the expected global warming contribution of bioenergy deployment. Several communities intensively debate these issues, widely diverging in their approaches and resulting estimates (Bright *et al.*, 2012; Schulze *et al.*, 2012; Searchinger, 2012; Haberl *et al.*, 2013b). The high variance in identified effects is mostly based in different boundaries of analysis. Crucially, when analytically boundaries reflect a wider variety of plausible assumptions, uncertainty increases considerably. For example, with wide boundaries of analysis and considering today's corn ethanol, the structural uncertainties become overwhelming and the net effect of bioenergy deployment could be net positive or net negative (Plevin *et al.*, 2010). Modeling long-term bioenergy futures, at least three effects, should be explicitly considered: first, the co-occurring emissions from fertilization and soil emissions; second, the market-induced emission from indirect land-use change, and the market-induced rebound effect in fossil fuels (Creutzig *et al.*, 2014); third, the baseline carbon opportunity costs for not allowing abandoned land to regrow forests.

It is important not to confuse foregone land carbon uptake with ILUC emissions. ILUC and rebound effects in fossil fuels are highly relevant (Creutzig & Kammen, 2010; Gawel & Ludwig, 2011; Plevin *et al.*, 2014) but can be excluded by assumptions in models – for example, by protection of global land carbon sinks and/or a global cap on GHG emissions – a courageous assumptions both on politics and, perhaps more importantly, on implementation. In contrast, land carbon stock dynamics represent biophysical processes and must be properly accounted for. The first two dimensions have been at least conceptually introduced into IAMs and their partnering land-use models (Wise *et al.*, 2009; Popp *et al.*, 2011). The third one has been only introduced into the IAM IMAGE (Vuuren *et al.*, 2013) and deserves further discussion.

The land carbon stock dynamics need to be contextualized with the net land carbon sink. The net land carbon sink is about 1.1 (0.4–1.8) PgC yr^{-1} in the 2000s (Khatiwala *et al.*, 2009), estimated by the balance between measured and modeled C-change in the atmosphere, overcompensating emissions from land-use change. Taking the United States as an example, noncrop, nonforest land absorbs about 0.11 PgC yr^{-1} on 300 Mha yr^{-1} or 36–39 gC m^{-2} (Pacala *et al.*, 2001). In units of carbon, integrated assessment models (ReMIND/MAgPIE; GCAM; IMAGE) foresee a productivity of primary energy (160–490 GJ ha^{-1} yr^{-1}) that in units of carbon fixation would correspond to 1.28–3.92 PgC yr^{-1} on 300 Mha or 430–1300 gC m^{-2} (assuming that 1 PgC corresponds to 37.5 EJ primary energy). The lower bound corresponds to assumed yield on marginal or abandoned land in the IMAGE model, roughly overlapping with the noncrop, nonforest land in Pacala *et al*., 2001;. In that case, the foregone land carbon fixation would be around 8.6% of the carbon uptake in the bioenergy case. In other words, the yield corresponds to 11 times the carbon fixation rate of the net primary productivity. Hence, the carbon opportunity costs are significant but small. If there were a newly emerging forest on this land, fixating 200 gC m^{-2} yr^{-1} over its first 50 years, carbon opportunity costs would amount to 47%. If yields were lower than modeled, and remain, in average, below NPP (a likely consideration according to Haberl *et al*. (2013a)), carbon opportunity costs could be higher. But under the high-yield assumptions in most IAM model runs, carbon opportunity costs remain low.

Van Vuuren *et al*. (2013) present an IAM that is sensitive to most of the concerns raised above. For example, in section 3, they discuss the feasibility of large-scale bioenergy deployment and the availability of CCS technologies, putting their assumptions into context. As a result, they assume a default land-use emission factor of 15 gCO_2/MJ produced bioenergy (based on some literature review and some calculation with their IAM mode, IMAGE), reducing the BECCS net effectiveness by about one-fifth. While other values could be equally argued for, this assumption is more appropriate than setting the emission factor implicitly to 0 gCO_2/MJ. Such an implicit assumption most likely leads to a systematic overestimation of the estimation potential of bioenergy, or alternatively, a systematic underestimation of the area needed for mitigation by bioenergy. Another example, reflecting insights from the ecological perspective, is Rose *et al*. (2014) who limit modern bioenergy deployment to 100 EJ yr^{-1} reflecting various ecological concerns.

The diet-shifting possibility, indicated for example in Edmonds *et al*. (2013), has potential downsides. In an unequal world, the affluent may well be able to continue paying for meat, while the global poor, who live on a mostly vegetarian diet to start with, get more deprived of food. Even as diet shift might be a desirable goal in terms of public health and climate mitigation, carbon-price-induced food price change could counter the original goals of climate change mitigation – improvement of human welfare, especially that of the most vulnerable. Hence, such assumptions deserve additional scrutiny.

Implications for negative emissions

What are the consequences of this discussion for negative emissions? The IPCC's AR5 has identified bioenergy with carbon capture and storage (BECCS) as a focal mitigation option to keep global warming below 2°C preindustrial levels. IAMs suggest that negative emissions from BECCS could accumulate to more than 270 PgC, essentially doubling the available emission budget (Fuss *et al*., 2014). For example, a recent study reports close to 160 PgC cumulative abatement until 2095 (Humpenöder *et al*., 2014). Here, BECCS becomes cost-competitive in 2065 and abates 5.5 Pg C yr^{-1}, limited by geological storage options. Crucially, the model (MAgPIE) assumes 1.38% annual yield improvements in its medium scenario. The resulting high-yield bioenergy plants can then deliver relatively low land-use primary energy, contributing to making BECCS competitive. But as reported above, yield growth is estimated to be lower in other literature. Specifically for the BECCS case, Kato & Yamagata (2014) perform a bottom-up assessment of required yield rates. They use the Soil and Water assessment tool (Nietsch *et al*., 2005) to find that only second generation biofuels, in particular miscanthus, would be sufficient to deliver a maximum of 3 Pg C yr^{-1} removal. Specifically, they assume that yields could increase indeed by more than 1.4%, but would level off after 2050. Miscanthus for BECCS would then imply a 77% increase in fertilizer application in 2100 (5.2 Pg C cumulative penalty). In comparison, Humpenöder *et al*. (2014) point to 8.2–13.6 Pg C in their model, corresponding to 120–200% increase in N_2O emissions over the century.

Two conclusions emerge from this particular comparison: (1) Yield assumptions are not only relevant for the plausibility of large-scale bioenergy deployment, but indirectly also for the feasibility of large-scale BECCS; (2) fertilizer input is a crucial variable determining the efficiency and sustainability of bioenergy and BECCS: On the one hand, fertilizer input would reduce the overall efficiency of carbon sequestration (at acceptable levels of less than 10%); on the other hand, the required fertilizer input could more than double from today's levels, while the global and local boundaries of the N cycle are already overstretched and affecting overall resilience of ecosystems via acidification of terrestrial ecosystems and eutrophication of coastal and freshwater systems (Rockström *et al*. 2009).

Another negative emission option, and alternative to BECCS, is an enhancement of the land carbon sink. Edmonds *et al*. (2013) report a net terrestrial carbon sequestration of 55–190 PgC between 2020 and 2095, resulting from afforestation as a response to a carbon price. But they do not specify the land, soil, water, and other resource requirements. Smith & Torn (2013) report that afforestation of 74 PgC over the same time frame would already require 200–1000 Mha of additional land (with higher probability on the higher end). This land requirement could harm food production and/or the remaining ecosystem services. Fertilizer input would increase fertilizer consumption by 20–75% above today's level, with considerable downstream consequences; water demand could further increase water stress in some world regions. Edmonds *et al.* (2013) again point to high expected yield increases that would reduce the scale of these problems. Smith and Torn discuss the case of 15 Mha afforestation per year. Edmonds *et al.* (2013, SOM) report 1800 Mha afforestation between 2015 and 2095 in their T1(Ref)xIdealized scenario (global cropland in the early 2000s extents to 1500Mha), corresponding to 22.5 Mha yr^{-1} on average, but with most land-use change occurring between 2020 and 2025 (around 200 Mha yr^{-1}, SOM fig. 7). It is unclear where these upfront around 1000 Mha would be coming from and what the systemic consequences on livelihoods and biodiversity would be. In their discussion of Smith & Torn (2013) in the special issue, Tavoni and Socolow conclude that 'this paper [. . .] raises the prospect that biological versions of carbon dioxide removal (CDR) may largely transfer environmental risk from the atmosphere to the land'.

The main result of Edmonds *et al.* (2013), Chen & Tavoni (2013), and Kriegler *et al.* (2013) is that carbon dioxide removal technologies like direct air capture, BECCS, and afforestation could produce negative emissions in the second half of the century and, by this, reduce emission reduction costs in the first half of the century. The results are specific to assumptions on climate stabilization scenarios, global cooperation, costs, and interaction with other technologies. Uncertainty on all these assumptions is very high. This uncertainty needs to be contrasted with the 'perfect foresight' in many IAMs, an assumption that implies that decision makers have perfect knowledge of future development given their decision. For example, Chen & Tavoni (2013) state: 'As WITCH assumes perfect foresight, policy makers look forward to negative emissions, and the result is more emissions in the near term and fewer in the long run'. But decision makers act under high structural uncertainty. Hence, CDR technologies need also to be investigated in light of robust decision making (Hall *et al.*, 2012; Kunreuther *et al.*, 2012), portfolio management (Fuss *et al.*, 2013), and/or Bayesian learning.

The most relevant overarching assumption might be that of institutional feasibility. To realize bioenergy as a low-carbon technology, land-use emissions (specifically ILUC) need to be avoided. In IAMs, this is typically realized by the assumption of a global carbon price, including a price on the land carbon stock. This not only requires a global agreement but also global enforcement on every hectare land. Common assumptions chosen in IAMs (200 EJ bioenergy available; carbon stock dynamics approximately irrelevant; ILUC can be avoided; BECCS cost competitive) display only a small sample of the overall assumption space, focusing on the corner of technological and political optimism.

Conclusion

This paper finds that a central result of the IPCC assessment – bioenergy and BECCS as main mitigation option – hinges on a few crucial assumptions in integrated assessment models. The discussion demonstrates that yield assumptions, in particular, take center stage and – while theoretically possible – remain speculative. Specifically, evidence suggests that yields grow linearly, not exponentially; that biophysical limits imply a leveling off of overall yields; and that in practice yields stay 50% of theoretically plausible yields. If high yields were to be achieved, the assumption of the integrated assessment models implies massive fertilizer application with likely harmful consequences for global and local ecosystems.

The different assumptions and emphasis in ecological studies and IAMs would translate into pointedly different outcomes. In high-yield worlds, both food production and bioenergy productions could be secured without compromising the land carbon stock, biodiversity, and livelihoods (Dornburg *et al.*, 2010; Popp *et al.*, 2011; Edmonds *et al.*, 2013). Ambitious climate mitigation targets become feasible aligning well with economic growth (Fischedick *et al.*, 2011). The availability of BECCS or other land-related CDR technologies would enable further climate mitigation (Edmonds *et al.*, 2013; Kriegler *et al.*, 2013). In contrast, if high yields are not realized in the presence of large-scale bioenergy deployment, harmful consequences are significantly more likely to occur as bioenergy relies on land as input factor compromising potentially other land uses. Specifically, land expansion might lead to high loss in land carbon stocks (Melillo *et al.*, 2009; Creutzig *et al.*, 2012a,b) and ecosystems and biodiversity deterioration might accelerate (Raghu *et al.*, 2006; Scharlemann & Laurance, 2008); alternatively, guaranteeing food security and livelihoods might become more challenging (Godfray *et al.*, 2010; Warner *et al.*, 2013), especially when integrating place-specific effects (Creutzig *et al.*, 2013; Hunsberger *et al.*, 2014). These diverging outcomes indicate the need of a proper discussion of which alternative assumption sets need to be tested to not only present the full solution space, but also the full possible assumption space.

This overall discussion (summarized in Table 1) reveals two different perspectives on future bioenergy

Table 1 Comparison between observations in ecological studies and assumptions in integrated assessment models

	Ecological studies	Integrated assessment models
Biomass yields	Anchored in average yields, observed growth rates and stationary NPP: <5 tC/yr/ha	Anchored in observed maximal obtainable yields or endogenous technological progress: 5–15 tC/yr/ha
Food crop yields	Growth rate: 0.7%; possibly linear; population growth and increased meat consumption lead to expanding land use for food	Growth rate: 1.4%, exponential; and/or diet shifts with less meat consumption allow for reduced land use for food
Accounting baseline	Foregone carbon uptake and induced ILUC induce potentially high relative reduction in the land carbon stock up to 100% carbon 'leakage'	Foregone carbon uptake ignored (exception: IMAGE) and ILUC excluded by assumption (forest and peatlands are protected) <10% carbon 'leakage' (if modeled at all)
Other impacts dimensions	Emphasizing exploitation of aquifers, pollution by fertilization, loss of non-monetary livelihood sources, and bioenergy; all of which need to be considered in conclusive studies on bioenergy potential	All dimensions are relevant but can be analytically separated and, hence, are mostly not part of model runs and their interpretation
Resolution	Focus on the particular, measured data, shorter time scales, and spatial analysis on all scales	Focus on economic dynamics, longer time scales, global aggregation of spatially explicit data, equilibrium effects

deployment. While both communities explicitly acknowledge the relevance of considering all factors, integrated assessment models tend to emphasize economic dynamics and long timescales, whereas ecological models are more grounded in biophysical processes and today's observations. The integrated assessment models see the global picture, the key relationships between aggregated factors, and ensuing equilibrium effects. The ecological community has a more particularistic approach and often identifies effects that appear on smaller spatial scales or by analyzing more detailed variables, and as a result sees more risks. An increased awareness of each others' intuition and analytical dimensions could benefit the overall assessment on bioenergy futures, iterating between formulating global strategies and managing particular risks.

Independent of the use of specific assumptions on bioenergy, this analysis suggests a modified use of IAMs for assessment making. First, studies would profit from shifting emphasis to presenting and discussing assumptions, and possibly their likelihoods. Second, studies could systematically analyze the robustness of proposed strategies by analyzing the risks of failure if certain conditions are not or only partially met. Third, promising strategies could include portfolio management and adaptive Bayesian learning. These modifications would allow a proper contextualization of the presented solution and would enable decision makers to fully hedge their strategies.

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References

Bright RM, Cherubini F, Astrup R *et al.* (2012) A comment to "Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral": Important insights beyond greenhouse gas accounting. *GCB Bioenergy*, **4**, 617–619.

Bruinsma J (2009) The resource outlook to 2050: By how much do land, water and crop yields need to increase by 2050? In: *How to Feed the World in 2050. Proceedings of a Technical Meeting of Experts, Rome, Italy, 24–26 June 2009*, pp. 1–33. Food and Agriculture Organization of the United Nations (FAO), Rome.

Bugmann H, Bigler C (2011) Will the CO_2 fertilization effect in forests be offset by reduced tree longevity? *Oecologia*, **165**, 533–544.

Chen C, Tavoni M (2013) Direct air capture of CO_2 and climate stabilization: a model based assessment. *Climatic Change*, **118**, 59–72.

Creutzig F, Kammen DM (2010) Getting the carbon out of transportation fuels. In: *Global Sustainability: a Nobel Cause* (ed. Schellnhuber HJ), Cambridge University Press, Cambridge.

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.

Creutzig F, Ravindranath N, Berndes G *et al.* (2014) Bioenergy and climate change mitigation: an assessment. *GCB Bioenergy*. doi: 10.1111/gcbb.12205.

DeLucia EH, Hamilton JG, Naidu SL *et al.* (1999) Net primary production of a forest ecosystem with experimental CO_2 enrichment. *Science*, **284**, 1177–1179.

DeWitte D (2009) *owa Corn Crop Poised to Set Record*. The Gazette, Cedar Rapids, Iowa, USA.

Dijkman TJ, Benders RMJ (2010) Comparison of renewable fuels based on their land use using energy densities. *Renewable and Sustainable Energy Reviews*, **14**, 3148–3155.

Dornburg V, van Vuuren D, van de Ven G *et al.* (2010) Bioenergy revisited: key factors in global potentials of bioenergy. *Energy & Environmental Science*, **3**, 258.

Duvick DN, Cassman KG (1999) Post–green revolution trends in yield potential of temperate maize in the North-Central United States. *Crop Science*, **39**, 1622–1630.

Edmonds J, Luckow P, Calvin K *et al.* (2013) Can radiative forcing be limited to 2.6 Wm-2 without negative emissions from bioenergy AND CO_2 capture and storage? *Climatic Change*, **118**, 29–43.

Elmore R, Abendroth L (2013) *Are We Capable of Producing 300 bu/acre Corn Yields?* Iowa State University, Ames, Iowa, USA.

Fargione J, Plevin R, Hill J (2010) The ecological impact of biofuels. *Annual Review of Ecology, Evolution and Systematics*, **41**, 351–377.

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

Fischedick M, Schaeffer R, Adedoyin A *et al.* (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, vonStechow C), Cambridge University Press, Cambridge, UK and New York, NY, USA.

Fuss S, Reuter W, Szolgayová J, Obersteiner M (2013) Optimal mitigation strategies with negative emission technologies and carbon sinks under uncertainty. *Climatic Change*, **118**, 73–87.

Fuss S, Canadell JG, Peters GP *et al.* (2014) Betting on negative emissions. *Nature Climate Change*, **4**, 850–853.

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.

Godfray HCJ, Beddington JR, Crute IR *et al.* (2010) Food security: the challenge of feeding 9 billion people. *Science*, **327**, 812–818.

Haberl H, Erb K-H, Krausmann F *et al.* (2007) Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. *Proceedings of the National Academy of Sciences of the United States of America*, **104**, 12942–12947.

Haberl H, Beringer T, Bhattacharya SC, Erb K-H, 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-H, Krausmann F, Running S, Searchinger T, Smith WK (2013a) Bioenergy: how much can we expect for 2050? *Environmental Research Letters*, **8**, 031004.

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

Hall JW, Lempert RJ, Keller K, Hackbarth A, Mijere C, McInerney DJ (2012) Robust climate policies under uncertainty: a comparison of robust decision making and info-gap methods. *Risk Analysis*, **32**, 1657–1672.

Heaton EA, Dohleman FG, Long SP (2008) Meeting US biofuel goals with less land: the potential of Miscanthus. *Global Change Biology*, **14**, 2000–2014.

Hong C, Fang J, Jin A *et al.* (2011) Comparative growth, biomass production and fuel properties among different perennial plants, bamboo and miscanthus. *The Botanical Review*, **77**, 197–207.

Hoogwijk MM (2004) *On the Global and Regional Potential of Renewable Energy Sources*. Universiteit Utrecht, Faculteit Scheikunde.

Hoogwijk M, Faaij PCA, 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.

Humpenöder F, Popp A, Dietrich JP *et al.* (2014) Investigating afforestation and bioenergy CCS as climate change mitigation strategies. *Environmental Research Letters*, **9**, 064029.

Hunsberger C, Bolwig S, Corbera E, Creutzig F (2014) Livelihood impacts of biofuel crop production: implications for governance. *Geoforum*, **54**, 248–260.

Kato E, Yamagata Y (2014) BECCS capability of dedicated bioenergy crops under a future land-use scenario targeting net negative carbon emissions. *Earth's Future*, **2**, 421–439.

Khatiwala S, Primeau F, Hall T (2009) Reconstruction of the history of anthropogenic CO_2 concentrations in the ocean. *Nature*, **462**, 346–349.

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.

Kunreuther H, Heal G, Allen M, Edenhofer O, Field CB, Yohe G (2012) Risk management and climate change. *Nature Climate Change*, **3**, 447–450.

Lewandowski I, Clifton-Brown JC, Scurlock JMO, Huisman W (2000) Miscanthus: European experience with a novel energy crop. *Biomass and Bioenergy*, **19**, 209–227.

Lobell DB, Schlenker W, Costa-Roberts J (2011) Climate trends and global crop production since 1980. *Science*, **333**, 616–620.

Melillo JM, Reilly JM, Kicklighter DW *et al.* (2009) Indirect emissions from biofuels: How important? *Science*, **326**, 1397–1399.

Meller L, vanVuuren DP, Cabeza M (2013) Quantifying biodiversity impacts of climate change and bioenergy: the role of integrated global scenarios. *Regional Environmental Change*, 1–11.

Moss RH, Edmonds JA, Hibbard KA *et al.* (2010) The next generation of scenarios for climate change research and assessment. *Nature*, **463**, 747–756.

Nietsch S, Arnold J, Kiniry J, Williams J, King K (2005) *Soil and Water Assessment Tool Theoretical Documentation*. *Version*. Texas Water Resource Institute, College Station, TX.

Pacala SW, Hurtt GC, Baker D *et al.* (2001) Consistent land-and atmosphere-based US carbon sink estimates. *Science*, **292**, 2316–2320.

Plevin RJ, O'Hare M, Jones AD, Torn MS, Gibbs HK (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 RJ, Delucchi MA, Creutzig F (2014) Using attributional life cycle assessment to estimate climate-change mitigation benefits misleads policy makers. *Journal of Industrial Ecology*, **18**, 73–83.

Popp A, Lotze-Campen H, Leimbach M, Knopf B, Beringer T, Bauer N, Bodirsky B (2011) On sustainability of bioenergy production: Integrating co-emissions from agricultural intensification. *Biomass and Bioenergy*, **35**, 4770–4780.

Popp A, Rose SK, Calvin K *et al.* (2014) 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.

Raghu S, Anderson RC, Daehler CC, Davis AS, Wiedenmann RN, Simberloff D, Mack RN (2006) Adding biofuels to the invasive species fire? *Science*, **313**, 1742.

Reich PB, Hobbie SE, Lee TD (2014) Plant growth enhancement by elevated CO_2 eliminated by joint water and nitrogen limitation. *Nature Geoscience*, **7**, 920–924.

Rockström J, Steffen W, Noone K, *et al.* (2009) A safe operating space for humanity. *Nature*, **461**, 472–475.

Rose SK, Kriegler E, Bibas R, Calvin K, Popp A, van Vuuren DP, Weyant J (2014) Bioenergy in energy transformation and climate management. *Climatic Change*, **123**, 477–493.

Scharlemann JP, Laurance WF (2008) How green are biofuels? *Science*, **319**, 43.

Schüler V, Weddige U, Beringer T, Gamba L, Lamers P (2013) Global biomass potentials under sustainability restrictions defined by the European Renewable Energy Directive 2009/28/EC. *GCB Bioenergy*, **5**, 652–663.

Schulze E-D, Körner C, Law BE, Haberl H, Luyssaert S (2012) Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral. *GCB Bioenergy*, **4**, 611–616.

Searchinger T (2012) Global Consequences of the Bioenergy Greenhouse Gas Accounting Error. In: *Energy, Transport, & the Environment*, pp. 679–711. Springer, London.

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

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

Smith P, Bustamente M, Ahammad H *et al.* (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, vonStechow C, Zwickel T, Minx J). Cambridge University Press, Cambridge, UK and New York, NY, USA.

Thomson AM, Izaurralde RC, West T, Parrish DJ, Tyler DD, Williams JR (2009) *Simulating Potential Switchgrass Production in the United States*. Pacific Northwest National Laboratory, Richland, WA.

Van Vuuren DP, Stehfest E, den Elzen MG *et al.* (2011) RCP2. 6: exploring the possibility to keep global mean temperature increase below 2 C. *Climatic Change*, **109**, 95–116.

Vuuren D, Deetman S, Vliet J, Berg M, Ruijven B, Koelbl B (2013) The role of negative CO_2 emissions for reaching 2 °C—insights from integrated assessment modelling. *Climatic Change*, **118**, 15–27.

Warner E, Inman D, Kunstman B *et al.* (2013) Modeling biofuel expansion effects on land use change dynamics. *Environmental Research Letters*, **8**, 015003.

Wise M, Calvin K, Thomson A *et al.* (2009) Implications of limiting CO_2 concentrations for land use and energy. *Science*, **324**, 1183–1186.