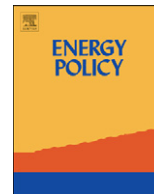




ELSEVIER

Contents lists available at SciVerse ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Viewpoint

Correcting a fundamental error in greenhouse gas accounting related to bioenergy

Helmut Haberl^{a,*}, Detlef Sprinz^b, Marc Bonazountas^c, Pierluigi Cocco^d, Yves Desaubies^e, Mogens Henze^f, Ole Hertel^g, Richard K. Johnson^h, Ulrike Kastrupⁱ, Pierre Laconte^j, Eckart Lange^k, Peter Novak^l, Jouni Paavola^m, Anette Reenbergⁿ, Sybille van den Hove^o, Theo Vermeire^p, Peter Wadhams^q, Timothy Searchinger^r

^a Institute of Social Ecology, Alpen-Adria Universitaet Klagenfurt, Wien, Graz, Schottenfeldgasse 29, 1070 Vienna, Austria

^b PIK-Potsdam Institute for Climate Impact Research, PO Box 60 12 03, D-14412 Potsdam, Germany

^c National Technical University of Athens, Iroon Polytechniou 5, 15780 Zografos, Greece

^d Department of Public Health, University of Cagliari, Asse Didattico — Policlinico Universitario SS 554, Km 4.500 09042 Monserrato (Cagliari), Italy

^e Mersea Conseil, Consultance Scientifique et Technique 3, avenue de Kerdivichen 29280, Locmaria – Plouzané, France

^f Technical University of Denmark, Department of Environmental Engineering, Miljøvej B113 – room 115/222, 2800 Kgs. Lyngby, Denmark

^g Department of Environmental Science, Aarhus University, P.O. Box 358, Frederiksborgvej 399, 4000 Roskilde, Denmark

^h Department of Aquatic Sciences and Assessment, Swedish University of Agricultural Sciences, Box 7050, 750 07 Uppsala, Sweden

ⁱ focus Terra-Earth Science Research & Information Centre, ETH Zurich, Sonneggstrasse 5, 8092 Zurich, Switzerland

^j Abdijdreef, 19, 3070 Kortenberg, Belgium

^k Department of Landscape, The University of Sheffield, Arts Tower, Western Bank, Sheffield S10 2 TN, United Kingdom

^l Faculty for High Technologies and Systems, Na Loko 2, 8000 Novo mesto, Slovenia

^m Sustainability Research Institute, University of Leeds, Leeds LS2 9JT, United Kingdom

ⁿ Department of Geography and Geology, University of Copenhagen Øster Volgade 10, 1350 Copenhagen K, Denmark

^o Median SCP, Passeig Pintor Romero, 8, 08197 Valldoreix (Barcelona), Spain

^p National Institute for Public Health and the Environment (RIVM), Antonie van Leeuwenhoeklaan 9, PO Box 1, 3720 BA Bilthoven, The Netherlands

^q Department of Applied Mathematics and Theoretical Physics (DAMTP), University of Cambridge, Wilberforce Road, Cambridge CB3 0WA, United Kingdom

^r Princeton University, Princeton, NJ 08544, USA

ARTICLE INFO

Article history:

Received 24 January 2012

Accepted 20 February 2012

Keywords:

Bioenergy

Greenhouse gas emissions

Greenhouse gas accounting

ABSTRACT

Many international policies encourage a switch from fossil fuels to bioenergy based on the premise that its use would not result in carbon accumulation in the atmosphere. Frequently cited bioenergy goals would at least double the present global human use of plant material, the production of which already requires the dedication of roughly 75% of vegetated lands and more than 70% of water withdrawals. However, burning biomass for energy provision increases the amount of carbon in the air just like burning coal, oil or gas if harvesting the biomass decreases the amount of carbon stored in plants and soils, or reduces carbon sequestration. Neglecting this fact results in an accounting error that could be corrected by considering that only the use of 'additional biomass' – biomass from additional plant growth or biomass that would decompose rapidly if not used for bioenergy – can reduce carbon emissions. Failure to correct this accounting flaw will likely have substantial adverse consequences. The article presents recommendations for correcting greenhouse gas accounts related to bioenergy.

© 2012 Elsevier Ltd. All rights reserved.

1. Introduction

Governments worldwide have implemented policies to promote bioenergy as a means both of reducing dependency on fossil energy and of reducing greenhouse gas (GHG) emissions. In our opinion, several of these policies – some European examples are discussed below – inaccurately assess the GHG emission consequences of

different forms of bioenergy and are likely to have serious adverse environmental consequences if not remedied (van Renssen, 2011).

This viewpoint article discusses the scientific background of an Opinion on bioenergy published in September 2011 by the Scientific Committee of the European Environment Agency (EEA).¹ In this article, 'bioenergy' refers to any energy produced by combusting

* Corresponding author. Tel.: +43 1 5224000 406; fax: +43 1 5224000 477.
E-mail address: helmut.haberl@aau.at (H. Haberl).

¹ <http://www.eea.europa.eu/about-us/governance/scientific-committee/sc-opinions/opinions-on-scientific-issues/sc-opinion-on-greenhouse-gas> (accessed: 2.1.2012).

biomass whether in solid form, such as wood chips or pellets burned for electricity; in liquid form, such as ethanol and biodiesel generated from crops or cellulose; or in gaseous form (biogas).

2. Bioenergy supply: Expectations and challenges

Correctly addressing the carbon implications of bioenergy is critical because a variety of studies and policies contemplate use of very large quantities of biomass in the belief that bioenergy is almost a GHG-neutral replacement for fossil fuels. Many projections imply at least doubling the total human harvest of world plant material. For example, the International Energy Agency has projected that bioenergy could supply over 20% of the world's primary energy by 2050 (IEA, 2008). A report by the Secretariat of the UNFCCC has claimed bioenergy can supply 800 EJ/yr (UNFCC Secretariat, 2008), which is far more than total world energy use today. The IPCC Special Report on Renewable Energy (SRREN) suggests that the global bioenergy potential could be as high as 500 EJ/yr (Chum et al., 2012), comparable to current fossil energy use. By contrast, the total global biomass harvest for food, feed, fibre, wood products, and traditional wood use for cooking and heat amounts to approximately 12 billion tonnes of dry matter of plant material per year (Krausmann et al., 2008) with a chemical energy value of 230 EJ.

An increase in the use of bioenergy of this magnitude could create substantial adverse impacts on natural ecosystems, compete with food production, and undermine other goals to reduce present impacts of agricultural production on the environment, and improve the well-being of farm animals (Erb et al., 2012; Haberl et al., 2011; Lambin and Meyfroidt, 2011; Smith et al., 2010). Ecosystems can be managed for satisfying human needs more or less sustainably, but all human uses of land and consumption of plants have environmental costs. Generating food, fiber and other biomass-based products that people currently consume utilizes roughly 75% of the world's vegetated land (Erb et al., 2007; UNEP, 2010). Agriculture, including livestock grazing, accounts for more than half of this area; in addition, a substantial fraction of the world's forests are managed for wood production. Moreover, over 70% of the water withdrawn from rivers and aquifers is used by agriculture (Comprehensive Assessment of Water Management in Agriculture, 2007). In addition, fertiliser use has doubled the amount of reactive nitrogen in the world, leading to large-scale pollution of aquatic ecosystems, extensive algal blooms and bodies of waters with low levels of oxygen (Erisman et al., 2008; Gruber and Galloway, 2008).

Even so, agricultural and forestry practices have not, on balance, increased the total quantity of biomass production: they have merely transformed natural ecosystems to produce goods and services for human consumption (Haberl et al., 2007). As human uses of land have already reached troubling levels (Foley et al., 2005, 2011; IAASTD, 2009; Millennium Ecosystem Assessment, 2005), and as large additional demands exist for food and timber (Smith et al., 2010), the challenges that would result from a doubling of global human biomass harvest for bioenergy (or even higher increases) should not be underestimated, and the full greenhouse gas emissions that would result from such an increase in bioenergy production are uncertain.

3. Correct greenhouse gas accounting

Many policies consider biomass combustion as 'carbon-neutral,' regardless of the source of the biomass. Although these policies may acknowledge the carbon emissions from using fossil fuels to produce and refine biomass, as well as trace-gases, they omit the carbon dioxide (CO₂) released by the burning of the biomass itself (Bird et al., 2011). They do so either by omitting

these emissions when accounting for emissions from bioenergy or by simply endorsing all bioenergy on the assumption that it emits no net carbon dioxide (Searchinger et al., 2009). Such policies and regulations thus treat biomass as an inherently 'carbon neutral' energy source. This is not correct.

Replacement of fossil sources of energy with biomass does not reduce GHG emissions from combustion. For example, burning one metric tonne of bone-dry wood will release about 1.8 t of CO₂ into the atmosphere. While bioenergy reduces or eliminates carbon emissions from fossil fuels, the combustion of biomass results in its own carbon emissions (Bird et al., 2011; Searchinger, 2010).

The assumption of carbon neutrality is often justified on the grounds that burning biomass only returns the carbon absorbed by growing plants to the atmosphere. Plants do absorb carbon, but this line of thought makes a 'baseline' error because it fails to recognize that if bioenergy were not produced, plants not harvested would continue to absorb carbon and help to reduce carbon in the air. Because that carbon reduction would occur anyway and is counted in global projections of atmospheric carbon, counting bioenergy that uses this carbon as carbon-neutral results in double-counting.

An example shows why. Imagine a hectare of cropland just abandoned and allowed to reforest. These growing plants would absorb carbon from the atmosphere to form plant tissue, i.e., biomass. Some of that biomass would be consumed and the carbon released by animals, fungi or microorganisms and would go back into the atmosphere. Other carbon would be stored in vegetation and soils as the forest grows, and that carbon absorption would have the effect of offsetting some of the emissions of carbon by burning fossil fuels and holding down global warming (Baldocchi, 2008; Le Quere et al., 2009; Richter et al., 2011). If the land were used instead to grow energy crops to be burned in a power plant, fossil fuel emissions would decline but not the carbon emitted by the power plant chimneys. Per unit of energy, the CO₂ emissions would typically even be higher than those of a fossil fuel-burning power plant because (i) biomass contains less energy per unit of carbon than petroleum products or natural gas do and (ii) biomass is usually burned with a lower efficiency than fossil fuels (Bird et al., 2011). Although the growth of bioenergy crops absorbs carbon, using the land to grow bioenergy crops sacrifices the sequestration of carbon in the forest. This foregone carbon sequestration, which is not considered in current GHG accounting related to bioenergy, may be substantial. For example, in the western Ukraine forest growth following abandonment of farmland resulted in a net carbon sink of almost one ton of carbon per hectare forest and year (Kuemmerle et al., 2011).

Simplifying the steps in this story, the decision to use the land for bioenergy results in more carbon being stored underground in fossil fuels, but this benefit comes at the expense of less carbon being stored by plants and soils. Bioenergy reduces CO₂ emissions only to the extent the first effect outweighs the second.

The use of food crops for the production of transportation biofuels provides a comparable story as they also absorb carbon whether used for bioenergy or not. Their use for bioenergy does not by itself result in additional plant growth, offset the emissions from energy use, or justify failing to account for the carbon emitted from exhaust pipes. This use of crops can only reduce carbon emissions through a series of 'indirect' market responses:

- Food crops do not usually keep carbon away from the atmosphere for long periods of time because they are consumed by people and livestock, who nourish themselves and thereby return almost all carbon to the atmosphere as respiration and waste. If food crops used for bioenergy are not replaced, there is a reduction in carbon emissions because people and livestock will release less CO₂ to the atmosphere, but that is not a desirable way of reducing GHGs.

Table 1Degree of likely accounting error when CO₂ emissions from biomass combustion are not properly considered.

Source of biomass	Degree of likely accounting error	Form of error
Converting forests currently sequestering carbon to bioenergy crops	Very high	Ignoring both immediate release of carbon and often continuing carbon sequestration of the forest if unharvested
Harvesting live trees for bioenergy and allowing forest to regrow	High	Same
Diverting crops or growing bioenergy crops on otherwise high-yielding agricultural land	High	Ignoring ongoing uptake of carbon on cropland and likely release of carbon in replacing the crops or reduced crop consumption
Using crop residues	Variable	Potentially ignores existing uses, need to replace nutrients, or potential effects on soil productivity (Blanco-Canqui and Lal, 2009)
Planting high-yielding energy crops on unused invasive grasslands	Low	Little or no error
Using post-harvest timber slash	Little or none	Could ignore temporal dimension of decomposition or existing uses
Using organic wastes otherwise deposited in landfill	Little or none	Little or no error

- If crops used for bioenergy are replaced by food production elsewhere, then the carbon emission consequences of bioenergy depend on how this is done. If more crops are grown on a unit of land, additional carbon is absorbed from the atmosphere.² If more land is converted to crops, then the calculation must include the lost carbon storage or sequestration due to changing land-use.

Only if, and to the extent to, these indirect effects are beneficial on balance could they justify ignoring some of the carbon emitted by the combustion of biomass such as biofuels.

It is important to be precise where and how physical changes occur in the absorption or emission of carbon in the use of bioenergy. Because bioenergy does not physically reduce emissions from exhausts, it must be true mathematically that bioenergy can reduce greenhouse gas emissions (except by reducing other human consumption of biomass, such as food) only if, and to the extent that:

1. land and plants are managed to grow additional biomass and take up additional CO₂ beyond what they would absorb without conversion into bioenergy, or
2. bioenergy production uses feedstocks, such as crop residues or wastes, that would otherwise decompose and release CO₂ to the atmosphere anyway.

To reiterate: only biomass grown in excess of that which would have grown anyway, or biomass that would otherwise have decomposed anyway, is 'additional biomass' containing 'additional carbon,' and has the potential to reduce carbon emissions when used for energy (Searchinger, 2010). The basic error in the carbon neutrality of biomass assumption is the failure to count the production and use of biomass that land would generate if not used for bioenergy (the counterfactual).

Correct GHG accounting needs to reflect not merely the loss of existing carbon stocks when biomass is produced and used for energy, but also any decline in carbon sequestration that would occur in the absence of bioenergy use. For example, forests particularly in the northern hemisphere are accumulating biomass for a variety of reasons (Erb et al., 2008; Pan et al., 2011; Richter et al., 2011) and this growth absorbs carbon from the atmosphere. Some estimates of bioenergy potential suggest that biomass reduces

greenhouse gas emissions so long as harvest is 'sustainable': if harvesting is kept below the level of forest growth, carbon stocks are argued to remain constant. But this line of reasoning ignores the additional carbon sequestration that would occur without wood harvesting for bioenergy (the counterfactual), which does not make bioenergy carbon neutral (Haberl et al., 2003; Holtsmark, in press).

If a forest is allowed to re-grow after harvest, it achieves approximately the same carbon storage level as an unharvested forest when the build-up of carbon stocks slows down and eventually stops as the forest reaches maturity.³ At that point, the use of the biomass becomes carbon-neutral. But achieving this parity may take decades or even centuries, which means that the CO₂ remains in the atmosphere for a long time before it is removed by plant growth, resulting in a 'pulse' of climate forcing that takes decades or centuries before being compensated by forest regrowth – thereby counteracting the goal of achieving GHG reductions in the next few decades (Cherubini et al., 2011a, 2011b). Increasing the harvest level in forests over longer time periods to achieve a sustained fuel wood flow permanently reduces the forest's carbon stock and thereby creates a 'carbon debt' that may require centuries to be repaid, even if forest area is conserved (Holtsmark, in press). Thus, to assess the consequences on global warming alone, accounting must assess the rates of plant growth with and without bioenergy production, and the changes induced by bioenergy production in the total amount of carbon stored in terrestrial plants and soils.

The studies projecting large quantities of bioenergy potential discussed above do not rule out double-counting of biomass already used or sequestering carbon and mostly neglect the true counterfactual. For example, large bioenergy potential estimates assume the availability of abandoned or unused agricultural land in present and future, but such land is not a free resource as its reversion to forest and grassland is a major component of the global terrestrial carbon sink (Pan et al., 2011). Bioenergy potential studies also call for harvesting forest carbon growth in excess of timber harvest, but that would also reduce the carbon sink and therefore add carbon to the air (Holtsmark, 2011). Nevertheless, there are indeed potential biomass sources that can reduce greenhouse gas emissions and that could be generated sustainably. Realistic expectations of such truly 'additional biomass' should be the focus of climate change strategies.

Table 1 highlights the likely advantageous and disadvantageous forms of biomass and the likely potential error in the

² Increasing yields through agricultural intensification often requires more inputs such as fertilizer which often result in higher GHG emissions. This must of course also be considered.

³ While this process is reasonably well understood for the aboveground component, uncertainties related to belowground carbon storage are larger.

existing directives of different forms of biomass highlights, showing that some bioenergy sources figuring prominently in current bioenergy policies are prone to be erroneously evaluated under current accounting rules.

4. Origins of the accounting error

The assumption that all biomass is carbon-neutral results from a misapplication of the original guidance provided for the national-level carbon accounting under the United Nations Framework Convention on Climate Change (UNFCCC). Under the UNFCCC accounting rules, countries report their emissions from energy use and from land-use change separately. For example, if a hectare of forest is cleared and the wood used for bioenergy, the carbon lost from the forest is counted as a land-use emission. To avoid double-counting, the rules therefore allow countries to ignore the same carbon when it is released after combustion. This accounting principle does not assume that biomass is carbon-neutral, but rather that emissions can be reported in the land-use sector. This accounting system is complete and accurate because emissions are reported from both land and energy sectors worldwide.

The accounting rule under the Kyoto Protocol is different: it caps emissions from energy use but does not apply worldwide and it applies only incompletely to land use even in the Annex I countries. By excluding biogenic emissions from the energy system, the Protocol erred because this practice means that those emissions are in many cases never accounted for at all. Similarly, many national and European policies and, as well as many lifecycle and other analyses, mistakenly ignore biogenic emissions from energy use without including changes in land-based carbon as a result of that bioenergy use.

5. European policies affected by the accounting error

In order to show how important these considerations are in a policy context, we focus on the example of Europe.⁴ European policies making this accounting error include at least:

- The European Union's Emissions Trading System⁵ (which caps emissions from major factories and power plants) ignores CO₂ emissions from biomass combustion but does not apply to land use;
- The Renewable Energy Directive⁶ (which requires that Member States increase their use of renewable energy to 20% by 2020) explicitly sets CO₂ emissions from biomass combustion to zero regardless of the source of the biomass.

The European Union has also adopted two Directives to promote transportation biofuels that at present fail to include

⁴ Europe was chosen as an example because most authors are Europeans. This choice should not be interpreted as a judgement of accounting standards in European bioenergy policies compared to those of other regions.

⁵ Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a system for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC, as subsequently amended. For full documentary history, see http://ec.europa.eu/clima/documentation/ets/index_en.htm, for an overview see http://ec.europa.eu/clima/policies/ets/index_en.htm.

⁶ DIRECTIVE 2009/28/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC.

proper GHG accounting:

- The renewable fuels portion of the Renewable Energy Directive,⁷ which requires that the Member States use qualifying renewable energy, which is expected to be almost exclusively biofuels, for 10% of their transportation fuel.
- The Fuel Quality Directive,⁸ which requires reductions in the carbon intensity of transportation fuels.

To measure GHG emissions related to bioenergy, these Directives use life-cycle analyses (LCA) that count emissions involved in growing crops and refining biofuels, as well as those from direct land use change, if a bioenergy crop is planted in a previously forested area or other high carbon ecosystems. But this accounting strategy still ignores the actual emissions of CO₂ by vehicles that use biofuels, without any assurance that the biomass is additional. If the bioenergy is supplied by crops grown on existing cropland, the analysis incorrectly assumes one of the following scenarios to be true: (i) this land would otherwise grow no plants, (ii) the crops it would generate are not replaced, or (iii) the crops are replaced entirely by intensifying planting and harvesting of existing cropland. If the crops are grown on grassland, the analysis counts the emissions from the conversion to cropland (i.e., carbon lost from soils and grass) but fails to assess the consequences of replacing the forage that this land would otherwise generate for livestock. Only a fully comprehensive accounting of indirect effects can fix this error. Even with proper accounting, care should be taken that biofuels are not credited with GHG reductions based on estimates that they will indirectly lead to reductions in food consumption.

Some people have suggested that as an alternative to accounting for indirect land use change, policymakers could use the same flawed accounting system but require that biofuels reduce greenhouse gas emissions by a higher percentage compared to fossil fuels, for example by 75% instead of the 50% that will be required in the EU Renewable Energy Directive. Doing so would not solve and could even exacerbate the problem. As long as the accounting ignores the CO₂ emissions from exhaust pipes without counting the indirect effects on land use, the accounting assumes that plant growth cancels out exhaust pipe emissions regardless of whether there is additional plant growth or reduced decomposition. Tighter thresholds will encourage making biofuels using more land, and more productive land (and perhaps even generate fewer litres of biofuels due to reduced yields), if doing so reduces GHG emissions from inputs (such as energy or fertiliser), even when the true consequences for greenhouse gases, hunger and biodiversity would be worse.

Although estimating the indirect consequences of biofuels is inherently uncertain, the proper alternative cannot be to assume that biomass is carbon free and emits no CO₂, which is the assumption in existing biofuels Directives. That approach is erroneous as the CO₂ emissions from the use of bioenergy are real and there may be no additional plant growth or reduced decomposition to compensate those emissions. We strongly recommend that any accounting system should fully quantify

⁷ DIRECTIVE 2009/28/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC (<http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0016:0062:en:PDF>).

⁸ Directive 2009/30/EC of the European Parliament and of the Council of 23 April 2009 amending Directive 98/70/EC as regards the specification of petrol, diesel and gas-oil and introducing a mechanism to monitor and reduce greenhouse gas emissions and amending Council Directive 1999/32/EC as regards the specification of fuel used by inland waterway vessels and repealing Directive 93/12/EEC (<http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32009L0030:EN:NOT>).

the greenhouse gas emissions attributable to the use of land, both direct and indirect, when evaluating the use of biofuels.

Recent developments in Europe indicate that political awareness of issues related to greenhouse gas accounting for bioenergy is rising. For instance, EU legislation such as the Renewable Energy Directive and the Fuel Quality Directive set out sustainability criteria for biofuels. More detailed provisions under the existing legislation are under discussion.⁹ We hope that the issues raised in this viewpoint will be taken up in the on-going political process in order to strengthen the environmental integrity of EU policies.

6. Recommendations

Based on the above-discussed considerations the authors recommend that:

- Policies and their goals should be revised to encourage bioenergy use only from additional biomass that reduces greenhouse gas emissions, without displacing other ecosystem services such as the provision of food and the production of fibre.
- Accounting standards for GHGs should count all the carbon and other GHGs releases by the combustion of carbon (as emissions), and should count as an offset additional plant growth or reduced decomposition of biomass, which together make up additional sequestration. The balance reflects the net effect of the production and use of bioenergy.
- Bioenergy policies should encourage energy production from biomass by-products, wastes and residues (except if those are needed to sustain soil fertility). Bioenergy policies should also promote the integrated production of biomass that adds to, rather than displaces, food production.
- Decision makers and stakeholders worldwide should adjust global expectations of bioenergy use and potential to levels based on the planet's capacity to generate additional biomass, without jeopardizing natural ecosystems.

Acknowledgements

We thank many colleagues for feedbacks and help, in particular Jan-Erik Petersen and Elena Ostariz of the EEA and Nadia Pinardi and Owen McIntyre (EEA Scientific Committee). We gratefully acknowledge funding by the Austrian Science Funds (FWF, project no. P20812-G11), the Austrian Academy of Sciences, VOLANTE project, the Austrian Ministry of Science and Research and an EU-FP7, (grant agreement no. 265104). The research presented here contributes to the Global Land Project (www.globallandproject.org).

References

Baldocchi, D., 2008. Breathing of the terrestrial biosphere: lessons learned from a global network of carbon dioxide flux measurement systems. *Australian Journal of Botany* 56, 1–26.

Bird, D.N., Pena, N., Zanchi, G., 2011. Zero, one, or in between: evaluation of alternative national and entity-level accounting for bioenergy. *GCB Bioenergy*. doi:10.1111/j.1757-1707.2011.01137.x.

Blanco-Canqui, H., Lal, R., 2009. Crop residue removal impacts on soil productivity and environmental quality. *Critical Reviews in Plant Sciences* 28, 139–163.

⁹ In 2010, for example, the European Commission adopted a report on sustainability requirements for the use of solid biomass and biogas in electricity, heating and cooling (EC, 2010). In the same year, the Joint Research Centre (JRC) published a study on indirect land-use change from biofuels (Edwards et al., 2010).

Cherubini, F., Peters, G.P., Berntsen, T., Strømman, A.H., Hertwich, E., 2011a. CO₂ emissions from biomass combustion for bioenergy: atmospheric decay and contribution to global warming. *GCB Bioenergy* 3, 413–426.

Cherubini, F., Strømman, A.H., Hertwich, E., 2011b. Effects of boreal forest management practices on the climate impact of CO₂ emissions from bioenergy. *Ecological Modelling* 223, 59–66.

Chum, H., Faaij, A., Moreira, J., Berndes, G., Dhamija, P., Gabrielle, B., Eng, A.G., Lucht, W., Makapo, M., Maserà Cerruti, O., McIntyre, T., Minowa, T., Pingoud, K., 2012. Bioenergy. In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S., Zwickel, T., Eickemeier, P., Hansen, G., Schlömer, S., von Stechow, C. (Eds.), *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*. Cambridge University Press, Cambridge, UK, pp. 209–332.

Comprehensive Assessment of Water Management in Agriculture, 2007. *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*. Earthscan. International Water Management Institute, London.

EC, 2010. Report from the Commission to the Council and European Parliament on sustainability requirements for the use of solid and gaseous biomass sources in electricity, heating and cooling. European Commission, COM(2010)11 final, Bruxelles.

Edwards, R., Mulligan, D., Marelli, L., 2010. Indirect land use change from increased biofuels demand – comparison of models and results for marginal biofuels production from different feedstocks, Joint Research Centre Technical Report, EUR 24485 EN. Publications Office of the European Union, Luxembourg.

Erb, K., Gingrich, S., Krausmann, F., Haberl, H., 2008. Industrialization, fossil fuels, and the transformation of land use. *Journal of Industrial Ecology* 12, 686–703.

Erb, K.-H., Gaube, V., Krausmann, F., Plutzer, 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.-H., Mayer, A., Krausmann, F., Lauk, C., Plutzer, C., Steinberger, J., Haberl, H., 2012. The interrelations of future global bioenergy potentials, food demand and agricultural technology. In: Gasparatos, A., Stromberg, P. (Eds.), *Socio-economic and Environmental Impacts of Biofuels: Evidence from Developing Nations*. Cambridge University Press, Cambridge, UK. in press.

Erisman, J.W., Sutton, M.A., Galloway, J., Klimont, Z., Winiwarter, W., 2008. How a century of ammonia synthesis changed the world. *Nature Geoscience* 1, 636–639.

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., Snyder, P.K., 2005. Global consequences of land use. *Science* 309, 570–574.

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockstrom, J., Sheehan, J., Siebert, S., Tilman, D., Zaks, D.P.M., 2011. Solutions for a cultivated planet. *Nature* 478, 337–342.

Gruber, N., Galloway, J.N., 2008. An earth-system perspective of the global nitrogen cycle. *Nature* 451, 293–296.

Haberl, H., Erb, K.-H., Krausmann, F., Adensam, H., Schulz, N., B., 2003. Land-use change and socio-economic metabolism in Austria—part II: Land-use scenarios for 2020. *Land Use Policy* 20, 21–39.

Haberl, H., Erb, K.H., Krausmann, F., Gaube, V., Bondeau, A., Plutzer, C., Gingrich, S., Lucht, W., Fischer-Kowalski, M., 2007. Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. *Proceedings of the National Academy of Sciences* 104, 12,942–12,947.

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

Holtmark, B. Harvesting in boreal forests and the biofuel carbon debt. *Climatic Change*, doi:10.1007/s10584-011-022-6, in press.

IAASTD, 2009. *Agriculture at a crossroads, International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD)*, Global Report. Island Press, Washington, D.C.

IEA, 2008. *Energy Technology Perspectives 2008, Scenarios and Strategies to 2050*. International Energy Agency (IEA), Paris.

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

Kuemmerle, T., Olofsson, P., Chaskovskyy, O., Baumann, M., Ostapowicz, K., Woodcock, C.E., Houghton, R.A., Hostert, P., Keeton, W.S., Radeloff, V.C., 2011. Post-Soviet farmland abandonment, forest recovery, and carbon sequestration in western Ukraine. *Global Change Biology* 17, 1335–1349.

Lambin, E.F., Meyfroidt, P., 2011. Global land use change, economic globalization, and the looming land scarcity. *Proceedings of the National Academy of Sciences* 108, 3465–3472.

Millennium Ecosystem Assessment, 2005. *Ecosystems and Human Well-being: Synthesis*. Island Press, Washington, DC.

Le Quere, C., Raupach, M.R., Canadell, J.G., Marland, G., et al., 2009. Trends in the sources and sinks of carbon dioxide. *Nature Geoscience* 2, 831–836.

Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S., McGuire, A.D., Piao, S., Rautiainen, A., Sitch, S., Hayes, D., 2011. A large and persistent carbon sink in the world's forests. *Science* 333, 988–993.

van Renssen, S., 2011. A biofuel conundrum. *Nature Climate Change* 1, 389–390.

- Richter, D., de, B., Houghton, R.A., 2011. Gross CO₂ fluxes from land-use change: implications for reducing global emissions and increasing sinks. *Carbon Management* 2, 41–47.
- Searchinger, T.D., 2010. Biofuels and the need for additional carbon. *Environmental Research Letters* 5, 024007.
- Searchinger, T.D., Hamburg, S.P., Melillo, J., Chameides, W., Havlik, P., Kammen, D.M., Likens, G.E., Lubowski, R.N., Obersteiner, M., Oppenheimer, M., Philip Robertson, G., Schlesinger, W.H., David Tilman, G., 2009. Fixing a critical climate accounting error. *Science* 326, 527–528.
- Smith, P., Gregory, P.J., van Vuuren, D., Obersteiner, M., Havlik, P., Rounsevell, M., Woods, J., Stehfest, E., Bellarby, J., 2010. Competition for land. *Philosophical Transactions of the Royal Society B: Biological Sciences* 365, 2941–2957.
- UNEP, 2010. GEO-4 Environment for Development. United Nations Environment Programme (UNEP), Nairobi, Kenya.
- UNFCC Secretariat, 2008. Challenges and opportunities for mitigation in the agricultural sector, Technical Paper. UNFCC FCCC/TP/2008/8, Geneva.