

Biofuels and the need for additional carbon

This article has been downloaded from IOPscience. Please scroll down to see the full text article.

2010 Environ. Res. Lett. 5 024007

(<http://iopscience.iop.org/1748-9326/5/2/024007>)

View [the table of contents for this issue](#), or go to the [journal homepage](#) for more

Download details:

IP Address: 99.30.227.134

The article was downloaded on 15/12/2010 at 02:28

Please note that [terms and conditions apply](#).

Biofuels and the need for additional carbon

Timothy D Searchinger

Princeton Environmental Institute and Woodrow Wilson School, Princeton University,
M27 Guyot Hall, Princeton, NJ 08544, USA

and

Transatlantic Fellow of the German Marshall Fund of the US, 1744 R Street, NW, Washington,
DC 20009, USA

E-mail: tsearchi@princeton.edu

Received 17 November 2009

Accepted for publication 5 May 2010

Published 1 June 2010

Online at stacks.iop.org/ERL/5/024007

Abstract

Use of biofuels does not reduce emissions from energy combustion but may offset emissions by increasing plant growth or by reducing plant residue or other non-energy emissions. To do so, biofuel production must generate and use ‘additional carbon’, which means carbon that plants would not otherwise absorb or that would be emitted to the atmosphere anyway. When biofuels cause no direct land use change, they use crops that would grow regardless of biofuels so they do not directly absorb additional carbon. All potential greenhouse gas reductions from such biofuels, as well as many potential emission increases, result from indirect effects, including reduced crop consumption, price-induced yield gains and land conversion. If lifecycle analyses ignore indirect effects of biofuels, they therefore cannot properly find greenhouse gas reductions. Uncertainties in estimating indirect emission reductions and increases are largely symmetrical. The failure to distinguish ‘additional’ carbon from carbon already absorbed or withheld from the atmosphere also leads to large overestimates of global bioenergy potential. Reasonable confidence in greenhouse gas reductions requires a precautionary approach to estimating indirect effects that does not rely on any single model. Reductions can be more directly assured, and other adverse indirect effects avoided, by focusing on biofuels from directly additional carbon.

Keywords: biofuels, land use change, climate change

 Online supplementary data available from stacks.iop.org/ERL/5/024007/mmedia

US and California law now require lifecycle analyses (LCAs) of greenhouse gas emissions from biofuels to consider land use change, whether direct or indirect—a position endorsed by a broad range of scientific bodies and technical agencies [1–8]. Direct land use change occurs if biofuel crops directly displace forest or pasture, releasing carbon from their plants and soils, whereas indirect land use change (ILUC) occurs when dedicating existing agricultural land to biofuels triggers market forces that lead to land conversion elsewhere to replace the food. Some biofuel researchers, companies and elected officials argue that while greenhouse gas analyses should reflect the emissions from direct land use change,

estimates of indirect emissions are too uncertain at this time to be incorporated into legal standards [9–12]. Based on this criticism, some Congressmen effectively insisted that the energy and climate bill passed by the US House of Representatives in July 2009 bar administrators from estimating international ILUC, and the European Union has so far excluded ILUC from its greenhouse gas calculations while it examines the issue this year [13].

This argument implicitly assumes that the greenhouse gas benefits from biofuels are direct and clear and therefore should not be clouded by uncertain costs. Even those who support counting ILUC generally do not challenge claims to

biofuels' direct greenhouse benefits [14]. Critics can also point to real uncertainties in the ILUC modeling estimates, acknowledged by the experts whose models have formed the basis for government calculations to date [15, 16].

The flaw in this claim is that when biofuels use existing crops, they produce no direct benefits. Biofuels can reduce greenhouse gas emissions from tailpipes by offsetting them with *additional* plant growth, but when they use existing crops, they by definition use carbon that plants would absorb anyway. Potential benefits can arise from using existing crops, but they are as indirect as ILUC carbon costs. LCAs that ignore ILUC make the same accounting error reflected in some treaties and laws of treating all biomass as carbon-free regardless of whether it is additional [17]. This paper explores the importance of 'additional' carbon capture in evaluating ILUC, in estimating bioenergy potential, and in formulating public policies.

1. The need for 'additional' carbon capture to reduce greenhouse gases

Advocates of biofuels typically state that biofuels reduce greenhouse gas emissions by reducing emissions from fossil fuels [18]. Yet cars burning biofuels emit roughly the same levels of CO₂ through their tailpipes as cars burning ethanol or diesel [17]. In the vehicle, biofuels just replace one source of emissions with another.

In a full LCA, greenhouse gas savings for biofuels could also exist if the emissions from growing and refining biomass ('production emissions') were lower than the production emissions from mining and refining crude oil. In reality, production emissions are typically higher for biofuels than for gasoline or diesel¹.

Biofuels instead have the potential to reduce greenhouse gases because growing plants for the fuel absorbs the carbon dioxide from the atmosphere that combustion ultimately releases. Based on this carbon origin, nearly all LCAs treat biofuels as 'carbon neutral'. That means the LCAs ignore tailpipe emissions from biofuels on the theory that plant growth cancels them out². By contrast, the LCAs do count the tailpipe emissions from the use of gasoline or diesel. This different treatment of tailpipe emissions accounts for all the potential greenhouse gas reductions of biofuels in traditional LCAs, i.e., those that ignore ILUC [17].

Although broadly understood, this key role of plant growth for biofuels is often underappreciated. It means that biofuels do not reduce total emissions from energy combustion but at best only offset them. By definition, an offset means an increase in carbon sinks (even if temporary) or a reduction in other kinds of emissions. In basic concept, using land to grow plants for biofuels to offset energy emissions is no different from using

land to offset those emissions by growing forests. Biofuels use the carbon taken up by the plants, the sink, to displace fossil fuels and thereby leave more carbon underground. Forest projects use the carbon uptake to increase sequestered carbon aboveground. Either way, a forest or any other plant cannot provide an offset if it already exists or would grow anyway; only additional plant growth provides an offset.

Energy offsets can also exist if they reduce other sources of emissions, as utilities might comply with emissions limits by paying for methane control at landfills. Bioenergy can reduce non-energy emissions by using otherwise rapidly decomposing timber or crop residues. That reduces emissions of CO₂ from the forest or cropland floor [17].

Put simply, biofuels can only reduce greenhouse gases if the biomass represents results from 'additional' carbon capture. Additional carbon means carbon that would otherwise be in the atmosphere if not incorporated in biomass used for fuel. The carbon must be captured either through additional plant growth or by saving biomass from being broken down through some other pathway.

2. Why greenhouse gas benefits from biofuels that use existing crops are as indirect and uncertain as ILUC costs

Biofuels use additional carbon, to provide two examples, if biofuel crops are grown by irrigating the desert (as illustrated in figure 1) or by planting abandoned cropland that would otherwise remain fallow or minimally productive. Each situation leads to increased plant growth. By contrast, if biofuel crops directly displace forests, there is probably no additional carbon [19–21]. The rate of carbon absorption by biofuel crops may not even match the carbon sequestration rate of the displaced forest, and the conversion itself releases carbon from forest plants and soils. Both situations involve direct land use change, which can be positive or negative on balance.

What happens when biofuels use existing crops, which means they do not directly change land use? By definition, that means the crops would be grown anyway. The short answer: because the diversion of existing crops to biofuels does not absorb any additional carbon from the atmosphere, there is no additional carbon. In that situation, the automatic assumption of an offset by plant growth is incorrect and there are no *direct* reductions in greenhouse gases.

These biofuels may still reduce greenhouse gas emissions, but any additional carbon and potential benefits occur 'indirectly'. In this context, indirectly means their benefits do not flow from the actions of the refiners or farmers generating the biofuel but from the market reactions of farmers and consumers around the world, who respond to higher crop prices caused by diverting crops to biofuels.

First, greenhouse gas reductions may occur if those price increases cause overall crop consumption for food and feed to decline. Crop growth absorbs carbon but does not sequester it for long because people and livestock eat and release the carbon. Mostly they metabolize the crops and breathe the carbon back into the atmosphere as CO₂, while they excrete

¹ Only 20% of gasoline emissions result from the production process, and those involved in the production process for most biofuels are typically estimated to exceed or match those of gasoline and diesel ([17, online supporting materials]).

² The GREET model counts the carbon emitted but credits the 'feedstock' with the carbon absorbed by the plants incorporated into the biofuel, which has the same effect [19].

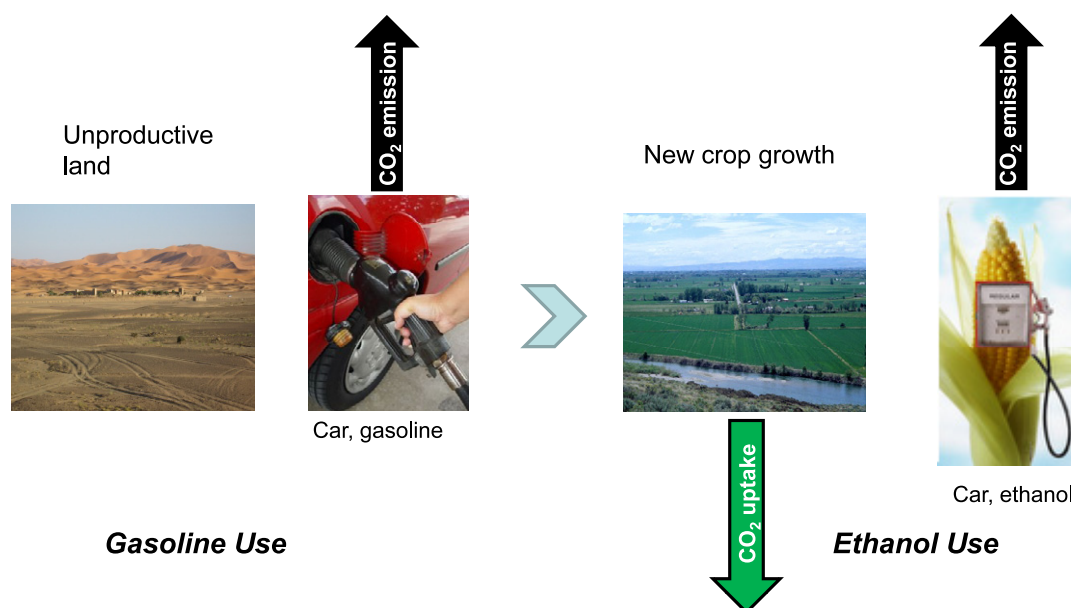


Figure 1. Effect of switching from gasoline to biofuels grown on otherwise unproductive land—reduced atmospheric CO₂ through increased plant growth.

some carbon as wastes and belch out some as methane. If people and livestock consume fewer crops, greenhouse gas reductions result from reduced respiration, methane and decomposition of these wastes.

It is possible to view this reduced consumption as a ‘direct reduction’ because the specific crops diverted to biofuels themselves are no longer consumed as feed and food. But the actual engines of emissions—people and livestock—do not consume less because of the loss of any particular crops. They only consume less because of higher prices. For the same reason, laws would not typically treat closing down any particular oil well as a source of carbon savings and credits.

Regardless of the nomenclature, few policymakers are likely to champion reduced food consumption as a desirable way of reducing greenhouse gases. Although some reductions occur for relatively benign reasons, such as improved animal feeding efficiency, others represent increased hunger. One modeling study estimates that one third of cereals diverted to ethanol would not be replaced because of reduced feed and food consumption [22]. In the analysis adopted by the State of California, some forms of corn ethanol achieved modest greenhouse gas benefits entirely because of reduced food consumption (online supporting materials available at stacks.iop.org/ERL/5/024007/mmedia). When California’s policies encourage such fuels, they unintentionally seek greenhouse gas reductions by reducing food use.

Second, farmers around the world may replace diverted crops by boosting their yields on existing farmland. Farmers will boost yields with or without biofuels, but higher crop prices may spur them to use more inputs, to double-crop or to adopt new technologies. The increase in production absorbs additional carbon from the atmosphere.

Boosting yields may also generate other greenhouse gases. According to data gathered by the Iowa Soybean Association, for example, Iowa farmers already use six to eight times more

nitrogen to generate the last bushel of corn than the average bushel. To the extent they replace corn diverted to ethanol by boosting fertilizer use, they probably generate emissions of more than 132 g (CO₂ eq.)/MJ of ethanol, which exceeds the likely emissions of replacing corn through land conversion (online supporting materials available at stacks.iop.org/ERL/5/024007/mmedia).

Finally, the world’s farmers may replace crops diverted to biofuels by plowing up new land from forest or grassland. Many of the potential benefits for biofuels result from the positive side of this ILUC as the new crops absorb carbon from the atmosphere. But ILUC also has negative effects through the reduced storage and sequestration of carbon in trees, grasses and soils, and potentially the loss of forage for livestock, which spurs further indirect effects. The net effect may increase or decrease greenhouse gas emissions, but the net effect is what counts [19–21].

The indirect increases in plant growth or reduced crop consumption generate what can be considered ‘indirect additional carbon’. Figures 2–5 illustrate the direct and indirect effects, which have a number of important lessons for LCAs from existing crops.

First, if indirect effects do not count, these biofuels cannot reduce greenhouse gases.

Second, when these biofuel LCAs ignore ILUC, they are not merely incomplete; they are incorrect because they ignore tailpipe emissions of CO₂ without justification as there is no additional plant growth to offset them.

Third, when LCAs incorporate ILUC, they are in reality calculating the extent to which the biofuel offsets tailpipe emissions indirectly, i.e., they are calculating ‘indirect additional carbon’. Indeed, the only ‘additional’ plant uptake of carbon results from the growth of crops to replace those diverted to biofuels, which is the positive side of indirect land

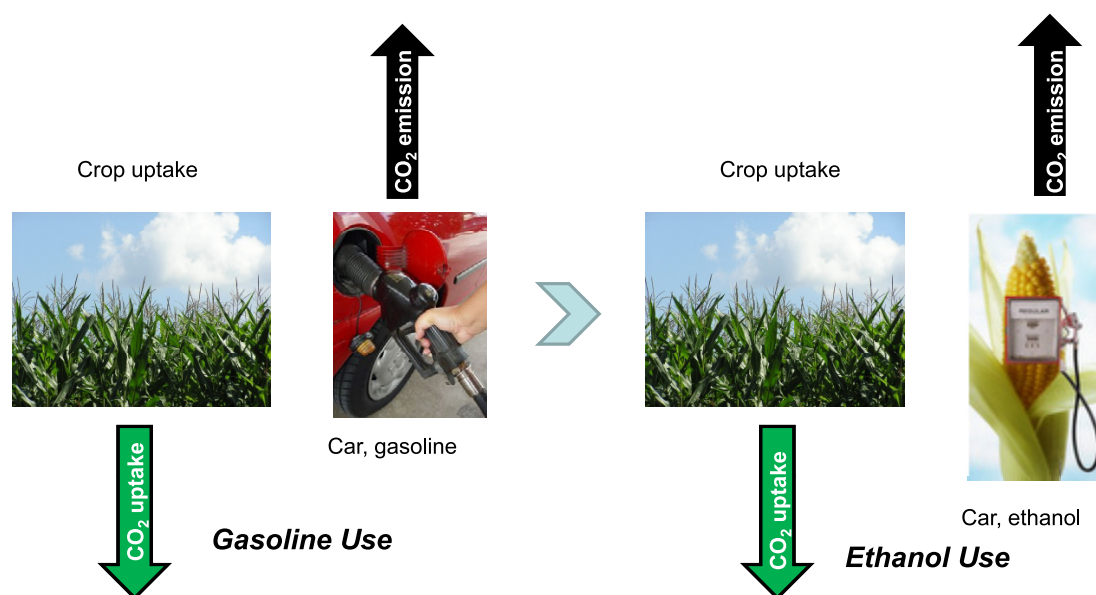


Figure 2. Direct effects of switching from gasoline to biofuels that use existing crops—no change in emissions.

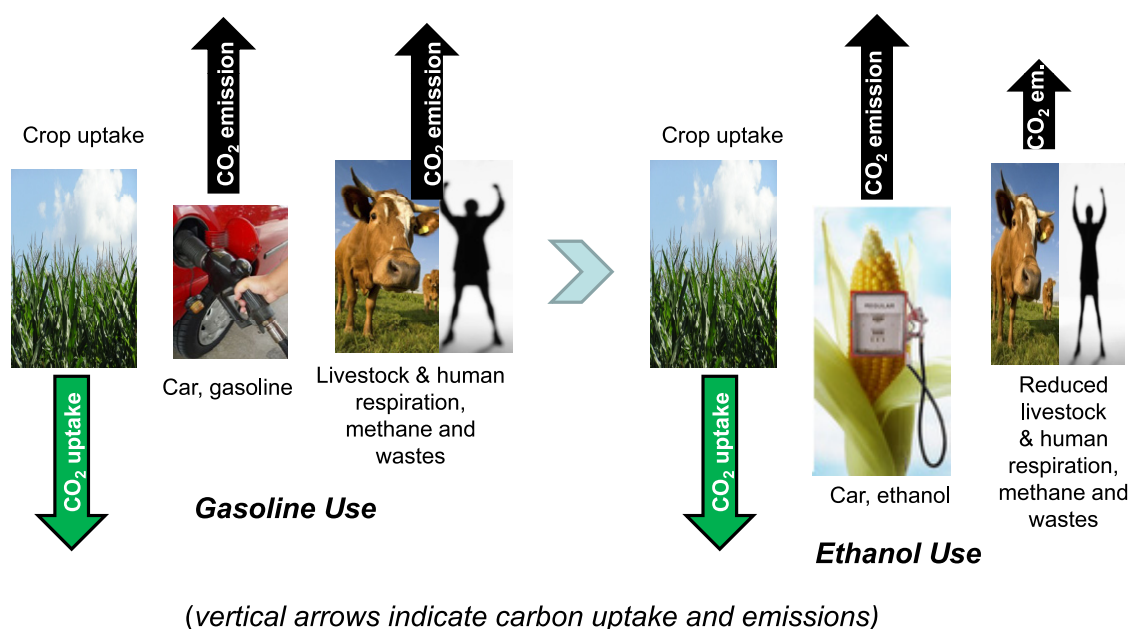


Figure 3. Indirect effect 1 of adopting ethanol—ethanol leads to less crop consumption for feed and food, which reduces CO₂.

conversion. An accurate analysis of land conversion must also reflect the carbon effects of losing the original vegetation³.

³ Technically, LCAs should ignore the carbon in grain used for ethanol as it would be grown anyway, which means they should count tailpipe emissions. LCAs should then assign a credit for the net land use effects, the additional carbon absorbed by replacement crops minus the effects of land conversion. Yet the difference between the carbon in crops used for ethanol and those grown in replacement crops is the carbon saved from reduced food consumption, which also provides a greenhouse gas benefit, and which should also be counted. When LCAs credit the carbon in crops used for ethanol and deduct the ILUC, they are inadvertently estimating the carbon in replacement crops plus the carbon emissions saved from reduced food consumption, which are the correct sources of 'additional carbon'. Although mathematically equivalent, this backward approach to the truth may obscure the policy implications of this analysis, such as treatment of reduced food consumption as a greenhouse gas benefit.

Fourth, because the different positive and negative indirect effects depend on each other, they are equally, and almost symmetrically uncertain. Indeed, the scope of ILUC depends on the relative rate of response to price increases of consumption declines, yield increases, and land conversion and estimating those different rates is the primary source of modeling uncertainty.

Finally, this analysis explains why counting ILUC does not unfairly 'blame' farmers for land use conversion abroad. Counting ILUC also does not unfairly single out biofuels from other land use activities, such as housing, that are not held accountable for their land use emissions. Because greenhouse gas reductions from biofuels are a form of land-based carbon offset, analyzing land effects is the only way

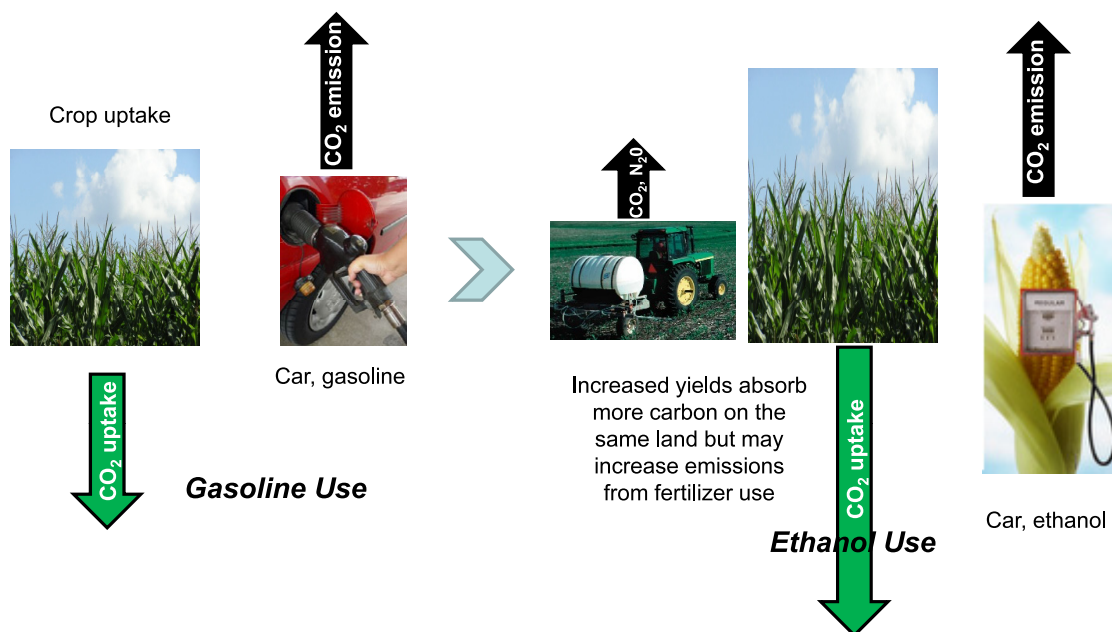


Figure 4. Indirect effect 2 of adopting ethanol—ethanol leads to yield growth on existing farmland to replace diverted crops, absorbing more carbon and probably reducing CO₂.

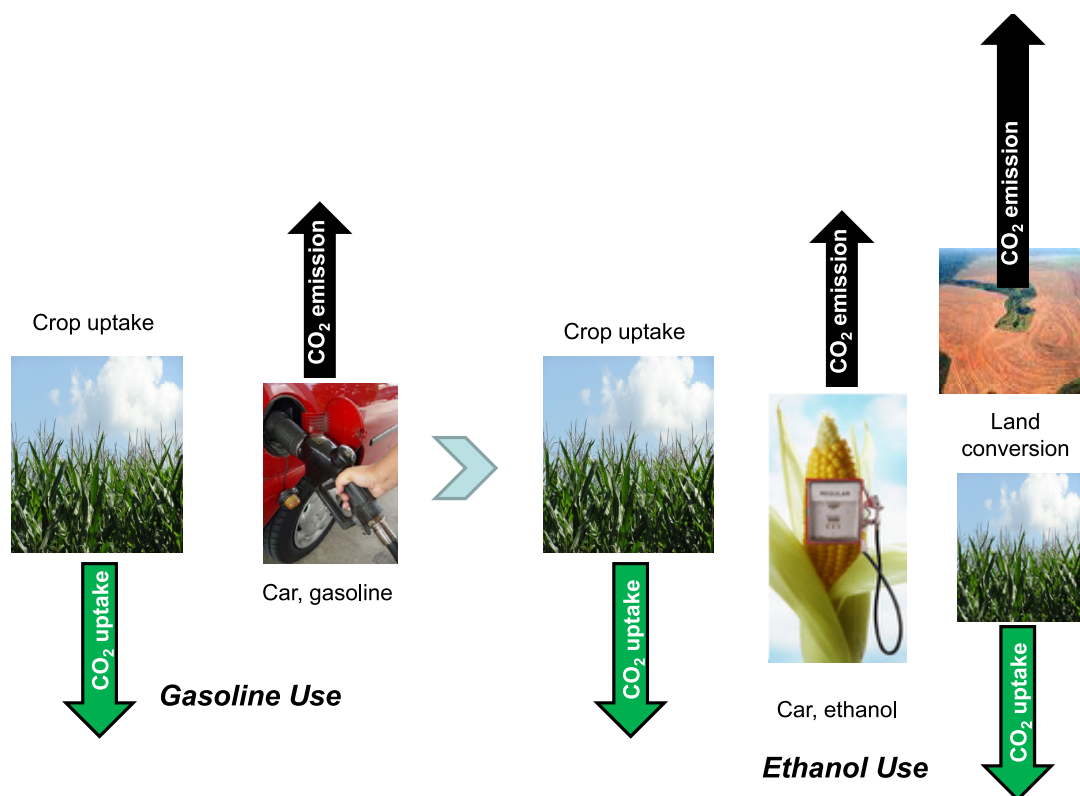


Figure 5. Indirect effect 3 of adopting ethanol—ethanol leads to land use change, which increases crop growth, but sacrifices forest or grassland and often causes net increase in CO₂.

of determining whether that offset exists. And far from blaming farmers, counting indirect effects is the only basis for rewarding biofuels from existing crops for greenhouse gas reductions in the first place.

3. Futility of counting direct but not indirect land use effects

The lack of direct, additional carbon when biofuels use existing crops creates a practical problem for regulations that ignore

ILUC. Even those who would ignore ILUC generally agree that biofuel policies should count emissions from direct land use change for biofuels [12]. For example, the existing European directive would count direct but not indirect land use change [13]. But regulating only these direct land use changes is likely to be futile.

To pick only a single possible example, palm oil expansion in Southeast Asia primarily to meet the world's voracious demand for food-grade vegetable oil is causing large-scale deforestation and releases of carbon from drained peat soils [23–25]. Palm oil can also supply biodiesel. Under the rule that counts direct but not indirect effects, a palm oil producer would be able to meet greenhouse gas criteria by storing in one tank all the palm oil now produced from already-cleared forests and selling that for biodiesel. The producer could then clear more forest and drain more peatland to replace the vegetable oil for food. So long as it stored that new palm oil in a second tank before selling it to the international food market, the producer would avoid direct land use change for the biodiesel. Such an easily bypassed protection would seem of little worth.

4. Distillers grains and potential improvements in the production process

Figures 1–5 are incomplete representations of ethanol because they leave out distillers grains (DGs) and production emissions, but the fuller picture does not alter the basic analysis.

DGs can absorb 30–40% of the carbon in the grain diverted to ethanol. This carbon is therefore not emitted as fuel, but it is fed to livestock and ultimately emitted or excreted by them. Because the livestock would emit this carbon even if fed the original grain instead of DGs, there is no direct change in carbon emitted. By effectively reducing the amount of grain diverted to energy use, DGs in effect reduce the amount of crops diverted to ethanol and therefore reduce the indirect effects of biofuels—and DGs and grain may have some differences in feed value⁴—but DGs do not provide additional carbon or reduce greenhouse gas emissions directly.

Second, roughly 25% of the chemical energy in grain fed into ethanol production helps power the fermentation process, causing emissions of CO₂ from the refinery itself [27]. LCAs ignore these emissions, like the tailpipe emissions, on the theory that biomass is carbon neutral, but these are real production emissions. The refining process typically also uses fossil energy, just as the refining of crude oil uses fossil energy, and LCAs do reflect these fossil fuel emissions. A variety of measures can increase the outputs from the energy used in refining ethanol and help 'close the loop', such as the use of the waste heat to raise livestock. However, the percentage of carbon released by the fermentation process itself exceeds the

roughly 20% of greenhouse gases emitted in the production process for gasoline [27]. Efficiencies in ethanol production can reduce biofuel emissions, but they are unlikely to ever decrease production emissions from ethanol to a level below those from gasoline.

Refiners can also use crop residues to replace fossil fuels in powering the refining process or drying DGs or to generate electricity. These changes reduce fossil fuel emissions but compensate with bioenergy emissions. LCAs typically ignore these emissions, as they ignore tailpipe emissions, on the grounds that they originate from biomass. That can generate greenhouse gas savings by displacing electricity from coal or other fossil fuels, which many LCAs then attribute to the biofuels, improving their greenhouse gas savings.

Again, because CO₂ emitted by refining and electricity generation is real, it should only be ignored to the extent additional carbon generates the biomass and offsets the emissions. Whether corn stover, bagasse and other residues provide additional carbon depends on their alternative uses. Even if they are wholly additional, meaning they would entirely decompose rapidly if not used for some form of bioenergy, crediting their greenhouse gas savings to the ethanol is only justified if the biomass would not be used for electricity production absent ethanol. That is only sometimes true.

As this analysis shows, by-products and potential improvements in ethanol production efficiency can affect the ultimate greenhouse gas balance of biofuels, but they will not directly produce additional carbon or greenhouse gas benefits.

5. Cellulosic biofuel crops

Energy crops such as switchgrass or miscanthus that replace food crops may utilize longer growing seasons to absorb more carbon, increasing net primary productivity (NPP) [28]. Should we think of this gain as 'additional' carbon?

On a global basis, crops are estimated to generate two thirds the NPP of the native vegetation they replaced [29]. This general sacrifice of NPP to grow crops is a carbon cost of using land to produce carbon in valuable, digestible forms. Replacing those crops on other lands, absent yield gains, would entail a similar 'carbon cost' that humanity has to pay somewhere so long as it wants edible carbon. For that reason, achieving higher NPP by using cropland for energy rather than food crops does not necessarily generate additional carbon.

If the food is replaced and if growing crops on the newly converted cropland entails a similar carbon cost, greenhouse reductions from energy crops only occur if the net effect of land use changes is positive, i.e., if the fossil fuel emissions saved by planting energy crops on cropland exceed the lost carbon storage and sequestration on land converted to replace the crops. When bioenergy crops use good cropland, large net reductions in this way are improbable. Using the GREET model, a high yield of 18 t ha⁻¹ y⁻¹ of switchgrass to produce ethanol at a high conversion efficiency of 341 l t⁻¹—higher than levels now broadly achieved—would reduce greenhouse gas emissions by 9.28 t CO₂ eq. ha⁻¹ y⁻¹ (not counting land use change). (Corn ethanol, after accounting for by-products yields savings of 3.4 t CO₂ eq. ha⁻¹ y⁻¹.) Land

⁴ Because DGs have high protein content, they can replace some high protein oilseed meals. Because the yields of oil seeds worldwide are lower than the yields of corn and wheat in the US and Europe, this higher substitution effect may reduce the ILUC, but a wide range of variables affect utilization and substitution rates ([26, pp C51–4]). That substitution affects ILUC calculation and can help generate indirect greenhouse gas reductions, but also does not serve as a direct source of greenhouse gas reductions.

wet enough to support these yields is wet enough to support forest. Sequestration in newly planted forests is likely to range from 7.5 to 12 t CO₂ ha⁻¹ y⁻¹ in temperate areas and 14 t to 28 t CO₂ ha⁻¹ y⁻¹ in the wet tropics, while conversion of existing tropical forests probably causes CO₂ releases of 12–30 t ha⁻¹ y⁻¹ on average over thirty years (online supporting materials available at stacks.iop.org/ERL/5/024007/mmedia). Even at twice the biomass yields, cellulosic ethanol might generate savings of 18 t CO₂ ha⁻¹ y⁻¹, but if the crop replacement sacrifices 10 t ha⁻¹ y⁻¹, the net gain is only 8 t CO₂ ha⁻¹ y⁻¹. When this net gain per hectare is apportioned to the ethanol it generates, net reductions compared to gasoline would be only 35% (online supporting materials available at stacks.iop.org/ERL/5/024007/mmedia).

Growing energy crops on grasslands requires a similar analysis. Nearly all new grazing land derives from forest [30]. If sugarcane or energy crops replace grasslands, but grasslands are replaced from forest, net gains are unlikely or at best modest [31].

The difference between using good cropland for biofuels and using relatively unproductive grazing land lies in the greater potential of replacing the food from the grazing land without converting other productive lands. Rainfed croplands of Europe and the US achieve an NPP that is far closer to the NPP of their native vegetation than average rainfed croplands worldwide, and that NPP is harvested efficiently for food [31, 32]. Because these croplands are already efficient uses of potential land productivity, they are costly from a carbon standpoint to replace. By contrast, some but by no means all grazing lands have low NPP relative to their native vegetation, and a smaller percentage of NPP of grasslands than croplands is harvested through livestock for human food [30, 31]. Because replacing the food should be easier, net gains from bioenergy crops on unproductive pastures should also be easier. Even so, achieving those gains without food loss depends on replacing their livestock products with little or no deforestation.

6. Global analyses of biofuel potential

Inaccurate estimates of bioenergy potential have resulted from the failure to distinguish ‘additional carbon’ from carbon otherwise stored or used.

For example, the IPCC’s analysis of biofuels for the Third Assessment estimated that biomass energy could provide 441 EJ of primary energy in 2050 ([33, table 3.31]), almost 90% of world energy use in 2007 [34]. That large potential existed even though the IPCC estimated an expansion of agricultural land by 416 million hectares for food production alone. To derive this biofuel potential estimate, the authors started with all potential world cropland, subtracted the cropland likely needed for food production in 2050, and assumed the rest could be devoted to biofuels. Unfortunately, the universe of potential, unused croplands consists of tropical forests, woodlots, savannahs and wetter grazing lands [35]. Using them for biofuels sacrifices carbon sequestration or food production with carbon emissions consequences.

Many recent analyses rely on subtler errors. For example, some papers view abandoned cropland as available land for sustainable biofuels [36, 37]. Depending on the scenario, Hoogwijk *et al* [36] estimate that over the next several decades, bioenergy can use between 600 million and 1.3 billion hectares of abandoned cropland, even in scenarios where total cropland increases and the abandoned cropland occurs because of shifts in cropland location. Using a common approach [38], Smeets [39] estimated large, sustainable bioenergy potential by counting all carbon growth in the world’s forests that is not needed for wood products (excluding forests reserved for wildlife). Both approaches play a prominent role in a 2009 estimate of bioenergy potential by the International Energy Agency (IEA) [40].

Yet if not used for biofuels, these abandoned croplands would probably sequester carbon through reforestation or grass growth. The re-growth of forests harvested decades ago would similarly sequester carbon. Both forms of carbon sequestration contribute heavily to the world’s terrestrial carbon sink [41], which by IPCC estimates absorbed 9.5 GT y⁻¹ of CO₂ in the 1990s, or roughly one quarter of annual greenhouse gas emissions [42]. Burning up carbon that would otherwise become sequestered does not reduce greenhouse gases. An estimate of ‘additional’ carbon potential has to focus only on any net gains of using abandoned lands for bioenergy.

Other papers have estimated bioenergy potential if large gains in crop yields and more efficient raising of livestock make surplus agricultural lands available for bioenergy crops [36, 39, 40, 42]. These estimates contrast with the more common view that agricultural land will have to expand to feed a larger population by 2050 that also consumes more meat [35, 43, p 63]. Regardless in this hypothetical scenario, the productivity gains themselves (net of emissions from additional inputs) are the sources of ‘additional’ carbon through increased carbon uptake by crops and reduced livestock consumption and emissions of carbon. These gains allow the NPP of more lands to be directed into carbon sequestration. Use of these hypothetical surplus lands for biofuels only reduces greenhouse gases to the extent it provides a greater offset than the carbon sequestration that would otherwise occur on these lands.

The IEA discusses two likely sources of additional biomass but incorrectly counts them as well. Crop and timber residues provide one such source, which the IEA estimates at 100 EJ [40], one fifth of the world’s primary energy use in 2007. But the basis of these high estimates is not only rough, reflecting broad estimates of crop or timber residues multiplied by assumed ‘recoverability’ percentages [38, p 16], they also do not exclude residues that are already used [39, pp 64–5]. As one 2003 review noted, ‘no study made any comprehensive assessment of residue generation or alternative residue uses (e.g., soil conservation and C sequestration, animal feeding and bedding, and paper/board production) in order to arrive at the residue multipliers and recoverability fractions used’ [38, p 16]. In reality, most of the world’s residues provide feed, bedding or energy [44, 45]. Even those left on the soil contribute nutrients and some soil carbon whose replacement triggers at least some other emissions.

At the national level, a few more careful and more modest projections exist of energy potential from residues [8, 46]. One still rough global estimate, which focuses only on unused residues, estimates a more modest 28 EJ of technical biofuel potential in 2050, not counting the energy costs of converting the biomass into liquid fuels [45].

The second source of potentially additional biomass is based on growing energy crops on 'low productivity lands' [36, 39, 40]. Yet again, these estimates typically include all the potential biomass produced on these lands. They should focus only on potential increases in plant growth on these lands.

These estimates mostly focus on wetter grazing land [36] or other non-forested lands that meet 'other' categories under FAO terminology and probably represent sparse woodlots and savannahs [36, 39, 40]. Some potential gains seem plausible, particularly among badly managed, tropical grasslands that were once forests. But if grazing lands are used, carbon reductions from biofuel use will require policies to assure corresponding gains in grazing productivity or livestock efficiencies to avoid knock-on expansion of cattle into forest and associated conversion.

The world unquestionably has underutilized, and degraded land, but estimates are rough [48]. Land is also generally used by someone, even if those uses do not show up well in land use data sets. Many wood lots and savannahs are centers of biodiversity, and studies tend to identify many of the same lands for both bioenergy and reforestation. Real field studies of real places are needed to determine the viability, appropriateness and net carbon gains of using specific 'low productivity lands' for bioenergy.

7. Should policy count on indirect additional carbon?

Policy is ultimately a matter of judgment, but correctly understanding the potential sources of greenhouse gas reductions from biofuels has important policy implications. A policy that seeks greenhouse gas reductions through biofuels from existing crops is a policy that in reality relies on indirectly generating additional carbon through crop price increases. Is such a policy wise?

Many technical agencies and scientific organizations in effect say no. Their reports recommend that biofuel policy focus on unused residues, cover crops, and perennial grasses grown on degraded land [1–8, 49]. These are all forms of directly additional carbon and do not compete with alternative uses of productive land. The reports offer two basic rationales.

First, many reports express concern about the consequences of even those 'indirect effects' that reduce emissions. Those consequences include reductions in food availability, and harm to biodiversity from clearing even lower carbon lands, such as savannahs. Price-induced yield increases are the most desirable indirect consequence of biofuel production, but they too have some negative consequences. They include added water pollution [50] and further depletion of water resources for irrigation in a world already suffering from a water crisis according to the United Nations [51]. Perhaps their

biggest consequence has not received attention. Most studies estimate that even without biofuels, yield increases worldwide will be insufficient to meet food demands without agricultural expansion [35, 43]. For that reason, even to the extent biofuels spur yield increases, biofuels make it harder to boost yields to meet growing food needs without deforestation.

Second, focusing on directly additional feedstocks avoids the risks that ILUC will undermine expected reductions in emissions. For example, if even 5–10% of vegetable oil diverted to biodiesel is replaced by palm oil grown on peatlands, the emissions from the decomposition of that peat alone would probably eliminate any gains from reduced fossil fuels (online supporting materials available at stacks.iop.org/ERL/5/024007/mmedia). Many experts view palm oil as the dominant source of future vegetable oil [52], and some estimates estimate a quarter of expanded palm oil production occurs on peatlands [53].

Put simply, if the uncertainty about indirect effects is a reason not to incorporate ILUC into greenhouse gas estimates for biofuels, then it is an equal reason not to rely on indirect effects as a source of greenhouse gas benefits. That is a reason to focus only on biofuels generated from directly additional carbon.

8. Dealing with ILUC uncertainty

National US and California law require quantitative estimates of greenhouse gas reductions from biofuels considering ILUC. Regulators have tried to provide them by using individual models to generate precise quantitative estimates of emissions. These methods correctly recognize the critical significance of ILUC but place too much reliance on individual models.

The quantitative uncertainties in model estimates are real. To start, there are limitations of economic methods. Some worldwide agricultural models are based on short-term supply and demand crop responses to price changes in different countries or sub-regions. These elasticities are difficult to calculate individually, and combining them magnifies potential errors. Short-term elasticities are almost certainly different from long-term elasticities. These models tend to leave out interactions between croplands and pasture. Finally, they mostly provide predictions of which countries or areas will increase crop production but not which kinds of lands they will use.

'Optimization' models initially assume land use decisions will maximize economic returns, but they use simplified production functions based on limited data for estimating costs and returns. The optimization of land use returns is also constrained in reality by political constraints and infrastructure. Some models limit the rate at which land use will change through simple formulae applied the same way everywhere with limited empirical origins. (For example, the GTAP model used by California assumes that potential crop yields on forest and grasslands are always equal within each agroecological zone, that land use change everywhere follows the same mathematical relationship based on relative rents and the percentage of land in different uses, and that the elasticity that drives this relationship in every region of the world today is the same as that gleaned from historic US experience [16].)

All models suffer from the uncertainty about whether past economic relationships will hold true in the future. They also must at least implicitly assume government land use policies that in reality can only be hypothesized. For example, models will generate different results based on whether they implicitly assume that governments will or will not build roads into forests or other carbon-rich areas to facilitate agricultural expansion⁵.

In reality, good models provide only plausible scenarios. Just as it would be a mistake to base climate policy on any one climate model, so it is a mistake to estimate ILUC from any one land use model. Multiple models instead should be compared and analyzed based on how they estimate key intermediate steps in the process including:

- (1) How much cropland for food is replaced by biofuel by-products?
- (2) How much diverted food is not replaced because of reduced consumption?
- (3) How much food is replaced by price-induced yields gains?
- (4) How much food is replaced by land expansion?
- (5) What kinds of lands in different locations provide the new cropland?
- (6) What yields do these new croplands have, and
- (7) How much carbon does each type of conversion release?

By comparing these intermediate estimates of different models, and analyzing their empirical basis, a reasonable range of final estimates is feasible. This process can support simplified, scenario-based analyses [55] that are transparent.

Yet uncertainties will remain. As in other areas of environmental policy, governments have to handle uncertainty. I would argue that a cautious approach is warranted to biofuels that use productive land and therefore rely on indirect effects for their benefits because of the risks of large emissions increases and the other potential adverse effects. By this thinking, policymakers would therefore be wise to assign emissions factors for ILUC that are high enough to provide a level of reasonable assurance that hoped for greenhouse gas reductions will be real.

9. Conclusion

Much biofuel policy and science have evolved from the incorrect assumption that the renewable nature of plant growth means the carbon emitted by biofuel combustion does not affect the climate. Renewable does not mean carbon is free. Bank accounts generate interest each year, but spending that interest still means the owner has less money remaining for other things. Land absorbs new carbon each year, but spending it on biofuels means giving it up for other purposes, including sequestration. One reasonable policy might promote only those biofuels that use feedstocks that directly result from additional carbon. At a minimum when biofuels use carbon from crops that would grow anyway and so do not provide direct greenhouse gas savings, estimates of indirect benefits should be cautious.

⁵ Often these policy judgments are unarticulated by the modelers, but in [54], the modelers illustrate how ILUC varies based on theoretically different government policies.

References

- [1] European Commission Joint Research Center 2008 *Biofuels in the European Context: Facts and Uncertainties* Ispra, Italy
- [2] Food & Agricultural Organization of the UN 2008 *The State of Food and Agriculture 2008: Biofuels: Prospects, Risks and Opportunities* Rome
- [3] International Energy Agency 2008 *Energy Technology Perspectives* Paris
- [4] OECD 2008 *Economic Assessment of Biofuel Support Policies*
- [5] Netherlands Environmental Assessment Agency 2008 *Local and Global Consequences of the EU Renewables Directive for Biofuels* Utrecht
- [6] UK Renewable Fuels Agency 2008 *The Gallagher Review of Indirect Effects of Biofuel Production* London
- [7] The Royal Society 2008 *Sustainable Biofuels: Prospects and Challenges* London
- [8] National Research Council 2009 *Liquid Transportation Fuels from Coal and Biomass: Technological Status, Costs, and Environmental Impacts* (Washington, DC: National Academy of Sciences)
- [9] Buis T, CEO Growth Energy 2009 *Prepared Testimony Before Agriculture Committee, US House of Representatives* available at <http://agriculture.house.gov/testimony/111/h052109/Buis.pdf> May 21
- [10] Peterson C 2009 Commentary: amendments to climate bill were necessary *Hutchinson Leader* available at www.hutchinsonleader.com/commentary-amendments-climate-change-bill-were-necessary-107 July 23
- [11] Bingaman J 2009 *Politico* available at www.politico.com/news/stories/0709/24783.html July 13
- [12] Simmons B et al 2008 *Letter to Mary D. Nichols, Chairman California Air Resources Board* June 24
- [13] Searchinger T 2009 Biofuels: environmental consequences and interactions with changing land use *Proc. Scientific Committee on Problems of the Environment (SCOPE) International Biofuels Project Rapid Assessment (Gummersbach, Sept. 2008)* ed H R Bringezu (Ithaca, NY: Cornell University Press) pp 37–52
- [14] Deluchi M et al 2008 *Letter to Mary D Nichols Chairman California Air Resources Board* July 3
- [15] Babcock B A 2009 Measuring Unmeasurable Land-Use Changes from Biofuels *Iowa Ag Rev.* 15 www.card.iastate.edu/iowa_ag_review/summer_09/article2.aspx
- [16] Hertel T et al 2009 *Supporting Online Materials for Global Land Use and Greenhouse Gas Emissions Impacts of US Maize Ethanol: The Role of Market-Mediated Responses* (West Lafayette, IN: Center for Global Trade Analysis, Purdue University) GTAP Working Paper No. 55
- [17] Searchinger T et al 2009 Fixing a critical climate accounting error *Science* 326 527–8
- [18] Dineen B 2009 Consensus in copenhagen? Replacing gasoline with biofuels *The Huffington Post* www.huffingtonpost.com/bob-dinneen/consensus-in-copenhagen-r_b_385784.html February 17
- [19] Searchinger T et al 2008 Use of US croplands for biofuels increases greenhouse gas emissions through land use change *Science* 319 1238–40
- [20] Fargione J, Hill J, Tilman D, Polasky S and Hawthorne P 2008 Land clearing and the biofuel carbon debt *Science* 319 1235–8
- [21] Gibbs H K, Johnston M, Foley J A, Holloway T, Monfreda C, Ramankutty N and Zaks D 2008 Carbon payback times for crop-based biofuel expansion in the tropics: the effects of changing yield and technology *Environ. Res. Lett.* 3 034001
- [22] Cornelissen S and Dehue B 2009 Summary of approaches to accounting for indirect impacts of biofuel production *Report to the Roundtable on Sustainable Biofuels* Ecofys, Utrecht, Netherlands
- [23] Koh L P and Wilcove D 2008 Is palm oil agriculture really destroying tropical biodiversity *Conserv. Lett.* 1 60–4

- [24] Hooijer A, Silvius M, Wösten H and Page S 2006 PEAT-CO₂, Assessment of CO₂ emissions from drained peatlands in SE Asia *Delft Hydraulics Report Q3943*
- [25] Page S E, Siegert F, Rieley J O, Boehm H, Jaya A and Limin S 2002 The amount of carbon released from peat and forest fires in Indonesia in 1997 *Nature* **420** 61–5
- [26] California Air Resources Board 2009 *Proposed Regulation to Implement the Low Carbon Fuel Standard* vol 2 Appendices (Sacramento, CA: California Air Resources Board) March 5
- [27] Ohlrogge J, Allen D, Berguson B, DellaPenna D, Shachar-Hill Y and Stymne S 2009 Driving on Biomass *Science* **324** 5930
- [28] Dohleman F and Long S 2009 More productive than maize in the midwest: how does miscanthus do it? *Plant Physiol.* **150** 2104–15
- [29] Haberl H, Erb K H, Kruasmann F, Gaube V, Bondeau A, Plutzar C, Gingrich S, Lucht W and Fischer-Kowalski M 2007 Quantifying and mapping the human appropriation of net primary production in the earth's terrestrial ecosystems *Proc. Natl Acad. Sci. USA* **104** 12492–47
- [30] Steinfeld H *et al* 2007 *Livestock's Long Shadow* (Rome: FAO)
- [31] Lapola D M *et al* 2010 Indirect land use changes can overcome carbon savings from biofuels in Brazil *Proc. Natl Acad. Sci. USA* **107** 3388–93
- [32] Foley J, Monfreda C, Ramankutty N and Zaks D 2007 Our share of the planetary pie *Proc. Natl Acad. Sci. USA* **104** 12585–6
- [33] Moomaw W R and Moreira J R 2001 Technical and economic potential of greenhouse gas emissions reduction *Climate Change 2001: Mitigation (Climate Change 2001 IPCC Third Assessment)* ed B Metz *et al* (New York: Cambridge University Press)
- [34] International Energy Agency 2009 *Key World Energy Statistics* Paris
- [35] Bruinsma J (ed) 2003 *World Agriculture: Toward 2015/30, An FAO Perspective* (Rome and London: FAO)
- [36] Hoogwijk M, Faaij A, Eickhout B, de Vries B and Turkenburg W 2005 Potential of biomass energy out to 2100 for four IPCC SRES land-use scenarios *Biomass Bioenergy* **29** 225–57
- [37] Dale V H, Kline K I, Wiens J and Fargione J 2010 *Biofuels Implications for Land Use* (Washington, DC: Ecological Society of America)
- [38] 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
- [39] Smeets E 2008 *Possibility and Limitations for Sustainable Bioenergy Production Systems* (Utrecht: Utrecht University)
- [40] Bauen M *et al* 2009 *Bioenergy—A Sustainable and Reliable Energy Source. A Review of Status and Prospects* (Paris: International Energy Agency)
- [41] Malhi Y, Meir P and Brown S 2002 Forests and global climate *Phil. Trans. R. Soc.* **360** 1567–91
- [42] Fischer G *et al* 2009 Biofuel production potentials in europe: sustainable use of cultivated lands and pastures, part II: land use scenarios *Biomass Bioenergy* **34** 173–87
- [43] Barker T *et al* 2007 Technical summary (2007) *Climate Change 2007: Mitigation (Contribution of Working Group III to the Fourth Assessment. Report of the Intergovernmental Panel on Climate Change)* ed B Metz, O R Davidson, P R Bosch, R Dave and L A Meyer (Cambridge: Cambridge University Press)
- [44] Smil V 1999 Crop residues: agriculture's largest harvest *BioScience* **49** 299–308
- [45] Erb K-H *et al* 2009 Eating the planet: feeding and fueling the world sustainably, fairly and humanely—a scoping study *Social Ecology Working Paper No. 116* www.uni-klu.ac.at/socec/downloads/WP116-WEB.pdf Vienna, Potsdam
- [46] Brander M *et al* 2009 *Methodology and Evidence Base on the Indirect Greenhouse Gas Effects of Using Wastes, Residues, and By-Products for Biofuels and Bioenergy, Report to the Renewables Fuels Agency and Department for Energy and Climate Change* (London: Econometrica)
- [47] International Energy Agency 2007 *Potential Contribution of Biofuel to the World's Energy Demand* Paris (Faaij A lead author)
- [48] Gibbs H K 2009 *Mapping the World's Degraded Land: A Synthesis of Databases and Methodologies* A background paper commissioned by The Nature Conservancy
- [49] Tilman D *et al* 2009 Beneficial biofuels—the food, energy, and environment trilemma *Science* **325** 270–1
- [50] Donner S and Kucharik C 2007 Corn-based ethanol production comprises goal of reducing nitrogen export to the mississippi river *Proc. Natl Acad. Sci. USA* **105** 4513–8
- [51] United Nations Educational Scientific and Cultural Organization 2006 *Water a Shared Responsibility; The United Nations World Water Development Report 2* Paris
- [52] Schmidt J H and Wedema B P 2008 Shift in the marginal supply of vegetable oil *Int. J. Life Cycle Assess.* **13** 235–9
- [53] Hooijer A, Silvius M, Wösten H and Page S 2006 PEAT-CO₂, assessment of CO₂ emissions from drained peatlands in SE Asia *Delft Hydraulics Report Q3943* Delft
- [54] Melillo J M *et al* 2009 Indirect emissions from biofuels: how important? *Science* **326** 1397–9
- [55] Searchinger T and Heimlich R 2009 Estimating greenhouse gas emissions from Soy-Based US biodiesel when factoring in emissions from land use change *Biofuels, Food and Feed Tradeoffs* (Oak Brook, IL: Farm Foundation) pp 45–55 www.farmfoundation.org/news/articlefiles/3714-Searchinger.pdf