nyas˙5457 nyas2010-v1.cls (1994/07/13 v1.2u Standard LaTeX document class) 1-29-2010 :1196

	NYAS	nyas˙5457-1504010	Dispatch: 1-29-2010	CE: WRV
aptara	Journal	MSP No.	No. of pages: 18	PE: Amanda/Carey

Ann. N.Y. Acad. Sci. ISSN 0077-8923

ANNALS OF THE NEW YORK ACADEMY OF SCIENCES

Impacts of biofuels on climate change, water use, and land use

Mark A. Delucchi

Institute of Transportation Studies, University of California, Davis, California, USA

Address for correspondence: Mark A. Delucchi, Research Scientist, Institute of Transportation Studies, University of

Q1 California, Davis, ~~CA~~, madelucchi@ucdavis.edu

Governments worldwide are promoting the development of biofuels in order to mitigate the climate impact of using fuels. In this article, I discuss the impacts of biofuels on climate change, water use, and land use. I discuss the overall metric by which these impacts have been measured and then present and discuss estimates of the impacts. In spite of the complexities of the environmental and technological systems that affect climate change, land use, and water use, and the difficulties of constructing useful metrics, it is possible to make some qualitative overall assessments. It is likely that biofuels produced from crops using conventional agricultural practices will *not* mitigate the impacts of climate change and will exacerbate stresses on water supplies, water quality, and land use, compared with petroleum fuels. Policies should promote the development of sustainable biofuel programs that have very low inputs of fossil fuels and chemicals that rely on rainfall or abundant groundwater, and that use land with little or no economic or ecological value in alternative uses.

Key words: biofuels; life-cycle analysis; climate change; water use; eutrophication; land use

Introduction and scope

Governments worldwide are promoting the development of biofuels, such as ethanol from corn, biodiesel from soybeans, and ethanol from wood or grass, in order to reduce dependency on oil imported from politically unstable regions of the world, spur agricultural development, and reduce the climate impact of fossil fuel combustion. Biofuels have been promoted as a way to mitigate the climate-change impacts of energy use because the carbon in a biofuel comes from the atmosphere, which means that the combustion of a biofuel returns to the atmosphere the amount of carbon dioxide (CO_2) that was removed by the growth of the biomass feedstock. Because CO_2 from the combustion of fossil fuels, such as oil, is one of the largest sources of anthropogenic climate-active "greenhouse gases" (GHGs), it might seem, at first blush, that the elimination of net CO_2 emissions from fuel combustion *per se*, as happens with biofuels, would help mitigate the potential for global climate change. It turns out, however, that this elimination of net CO_2 emissions is a relatively small part of a complete accounting of the climate impacts of biofuels. Indeed, as I shall delineate here, calculating the climate impact of biofuels is so complex, and our understanding is so incomplete, that we can make only general qualitative statements about the overall impact of biofuels on climate. Moreover, the production of biofuels can have significant impacts on water use, water quality, and land use—because per unit of energy produced, biofuels require orders of magnitude more land and water than do petroleum transportation fuels—and these impacts should be weighed in an overall assessment of the costs and benefits of policies that promote biofuels.

In this article, I discuss the impacts of biofuels on climate change, water use, and land use. I focus on biofuels for transport, and not bioelectricity, because biofuels are being promoted mainly as substitutes for gasoline and diesel fuel.[a] I do not consider analyses of lifecycle energy use,[2–5] because we care

[a]For a recent integrated lifecycle assessment of bioelectricity technologies, considering a wide range of environmental indicators including GHG emissions, air pollutant emissions, and land-use efficiency, see Thornley *et al.*[1]

doi: 10.1111/j.1749-6632.2010.05457.x

not about energy use *per se*, but rather about things that energy use is related to, such as economic and environmental impacts, and here I directly examine impacts.[b] Finally, I do not consider issues associated with the use of chemicals in biofuel lifecycles.[c]

At the start of each major section (climate impacts, water impacts, and land use), I first discuss the overall metric by which impacts will be measured. This overall metric is important because many analysts use it is a basis for evaluating and comparing the impacts of biofuels; hence, the overall metric should be as broad as possible yet still represent what society cares about. I argue that the absence of broad, meaningful metrics for climate-change, water-use, and land-use impacts makes overall evaluations difficult. For example, in the case of climate-change impacts, virtually all researchers have used the same metric, CO_2-equivalent (CO_2e) emissions based on "Global Warming Potentials" (GWPs), but there are serious shortcomings with CO_2e factors based on GWPs. In the case of land use, the common metric—the area of land used—is straightforward to estimate and understand, but is only indirectly related to things that we care about, such as prices of agricultural land and the preservation of natural land. And in the case of water use, the available metrics are just rough indicators of the real impacts on water availability and water quality.

Nonetheless, in spite of the complexities of the environmental and technological systems that affect climate change, land use, and water use, and the difficulties of constructing useful metrics, we are able to make some qualitative overall assessments. It is likely that biofuels produced from crops using conventional agricultural practices will *not* mitigate the impacts of climate change and will exacerbate stresses on water supplies, water quality, and land use, compared with petroleum fuels. Policies should promote the development of sustainable biofuel programs that have very low inputs of fossil fuels and chemicals that rely on rainfall or abundant groundwater, and that use land with little or no economic or ecological value in alternative uses.

[b] Because some of the impacts of biofuel use are directly correlated with energy use, energy-use measures can serve as a proxy when estimates of the actual impacts of concern are not available.[3] Similarly, energy use and related measures can be useful for telling engineers where to concentrate on improving efficiency,[4] but this is not our concern here.

[c] For an analysis of the contribution of chemicals to the lifecycle of ethanol, see MacLean and Spatari.[6]

Climate-change impacts of biofuels

Over the past 20 years, researchers have performed hundreds of analyses of CO_2e GHG emissions from the lifecycle of biofuels. These analyses typically have estimated emissions of CO_2, methane (CH_4), and nitrous oxide (N_2O) emitted from the production of biofuel feedstocks (e.g., growing corn), the production of the biofuel (e.g., producing ethanol from corn), and the distribution and end-use of the biofuels (e.g., the use of ethanol in motor vehicles). Analysts multiply emissions of CH_4 and N_2O by their respective GWPs and add the result to estimated emissions of CO_2 to produce a measure of total lifecycle CO_2e GHG emissions. Several recent reviews discuss LCA of biofuels, results from biofuel ~~LCAs,~~ and issues in biofuel LCA.[7–17] Here, I discuss Q2 problems with the CO_2e metric, well-known and emerging issues in conventional LCAs, and other potentially important issues.

Problems with the CO_2e metric

As mentioned above, virtually all biofuel LCAs measure the climate impact of biofuels on the basis of the GWP of CO_2, CH_4, and N_2O emissions. The GWP estimates the radiative forcing of gas i (e.g., CH_4) relative to that of CO_2 integrated (typically) over a 100-year period, accounting for the decay of the gas in the atmosphere and the direct and indirect radiative forcing.[18] Hence, biofuel LCAs estimate the total relative radiative forcing over a 100-year period, for three GHGs.

There are several problems with this metric.[18–27] First, we care about the impacts of climate change, not about radiative forcing *per se*, and changes in radiative forcing are not simply (linearly) correlated with changes in climate impacts. Second, the method for calculating the GWPs involves several unrealistic simplifying assumptions, which can be avoided relatively easily. Third, by integrating radiative forcing from the present day to 100 years hence, the GWPs in effect give a weight of 1.0 to every year between now and 100 and a weight of 0.0 to every year beyond 100, which certainly does not reflect how society makes trade-offs over time (a more realistic treatment would use continuous discounting). Fourth, the conventional method omits several gases and aerosols that are emitted in significant quantities from biofuel lifecycles and can have a significant impact on climate, such as ozone precursors, carbon monoxide (CO), nitrogen oxides (NO_X), sulfur oxides (SO_X), and black carbon (BC).

Some preliminary work indicates that a method for estimating CO_2e factors that addresses the shortcomings above can produce comparative assessments that are appreciably different from those that use traditional GWPs and consider only CO_2, CH_4, and N_2O.[14,28]

Well-known and emerging issues in conventional biofuel LCA

In most biofuel LCAs, the estimated CO_2e climate impact (based on GWPs, as discussed above) is a function of four factors, the first three of which have long been known, and the fourth of which is an important emerging issue:[7–10,29] (1) the amount and kind of fossil fuel used in cultivation of biomass feedstocks and in the production of the biofuel; (2) the amount of nitrogen fertilizer applied, and the assumptions regarding N_2O emissions from that fertilizer;[d] (3) the benefits of any coproducts of the biofuel production process (e.g., animal feed is produced along with ethanol in corn-to-ethanol plants); and (4) the assumptions and analytical methods concerning carbon emissions from land-use change (LUC).[e] As Börjesson[10] notes, "depending on these four factors, production systems for ethanol may mean anything from major climate benefits to increased emissions of GHG compared with petrol" (p. 593).

Börjesson's[10] conclusion, however, applies mainly to biofuels derived from agricultural crops such as corn, soybeans, and wheat—so-called "first-generation" biofuels. It certainly does not apply to biofuels derived from waste products[f] (which are usually available only in small quantities), and it applies with less force to so-called "second-generation" biofuels derived from cellulosic sources such as grasses and trees. Compared with biofuels from agricultural crops, cellulosic biofuels generally require less fertilizer (and hence produce less N_2O), use nonfossil sources of energy (such as part of the plant material) in the production of the biofuel (and hence do not emit fossil CO_2), and in some circumstances cause lower emissions related to LUC on account of the relatively high carbon stocks maintained in the soils and biomass of grass and wood plantations. In the best case, if cellulosic biofuels are derived from mixed grasses grown on degraded lands with little management and low inputs,[38] lifecycle CO_2e emissions almost certainly will be lower than from petroleum fuels.[g]

[d] Most analyses estimate N_2O emissions by applying emission factors, for example, in grams of N-N_2O per gram of N fertilizer, to assumed fertilizer N application (see IPCC[30] for emission factors). A few have used biogeochemical models of C, N_2O, and CH_4 cycling in soils to assess greenhouse-gas emissions from bioenergy cropping systems.[31] By contrast, Crutzen *et al.*[32] estimate N_2O emissions from agriculture using a "top-down" approach, based on the observed increases in atmospheric N_2O, and calculate an emission rate twice that implied by the IPCC[30] emission factors: about 4% conversion of N-fertilizer to N-N_2O versus 2% or less based on IPCC[30] emission factors applied to all direct and indirect sources, including human sewage. To resolve this discrepancy, Davidson[33] combines a top-down analysis of historic atmospheric accumulation of N_2O with "bottom-up" emission factor estimates of N_2O from transportation and industrial sources, for the period from 1860 to 2005, and finds that 2.5% of fertilizer N is converted to N-N_2O. Davidson[33] suggests that the model of Crutzen *et al.*[32] explains the 2 years for which it was calibrated (1860 and 1995), but does not work for the period between those years.

[e] The carbon content of soils and biomass on uncultivated land generally is higher than the carbon content of cultivated land, and thus to the extent that the development of biofuels causes an expansion of agriculture into previously uncultivated areas, there can be large emissions of carbon from soils and biomass.[34] These C emissions due to LUC can be large relative to the CO_2e emissions from the rest of the biofuels lifecycle.[35,36]

[f] Note that here I refer to true waste products, which have no alternative use whatsoever. Agricultural and forestry residues are not wastes, because they perform important services in agricultural and forests ecosystems.[37]

[g] It is important to note that a proper comparison of biofuels with petroleum fuels does not necessarily assume that the degraded land used in the biofuel case would be left degraded in the (no-biofuels) petroleum fuel case. Rather, in the (no-biofuels) petroleum case, it reasonably could be assumed that the land would be restored to a native ecosystem of high ecological value.[39]

Potentially important issues that have not been investigated in the context of biofuel LCA

The production of biofuels will cause at least two kinds of changes in the environment that are likely to have major impacts on climate but that have not yet been included in any published biofuel LCAs: changes in biogeophysical parameters due to changes in land use, and perturbations to the nitrogen cycle due to the use of nitrogen fertilizer.

Biogeophysical impacts

Changes in land use and vegetation can change physical parameters, such as albedo (reflectivity) and evapotranspiration rates, that directly affect the absorption and disposition of energy at the surface of the earth and thereby affect local and regional temperatures.[40–47] Changes in temperature and evapotranspiration can affect the hydrologic cycle,[48] which in turn can affect ecosystems and climate in several ways, for example, via the direct radiative forcing of water vapor, via evapotranspirative cooling, via cloud formation, or via rainfall, affecting the growth and hence carbon sequestration by plants.

Because of the higher albedo and higher evapotranspiration of many crops, the conversion of midlatitude (e.g., North American) forests and grasslands to agriculture generally will reduce regional temperatures.[41] On the other hand, the biogeophysical effects of a conversion of broadleaf tropical forests to agriculture will lead to a significant warming.[41] Lamptey *et al.*[45] use a regional climate model with a land surface scheme to investigate the effects of urban land and agricultural land on climate in the northeastern United States, and find that a conversion of forests to agriculture reduces temperature in winter, due to the lower albedo of forests in winter (snow, which has a high albedo, covers croplands but not forests, which poke through the snow), but increases temperatures in summer, due to reduced evaporation (crops have smaller leaf area indices and shallower roots, which prevent them from having access to soil moisture).

In some cases, the climate impacts of changes in albedo and evapotranspiration due to LUC appear to be of the same order of magnitude but of the opposite sign as the climate impacts that result from the associated changes in carbon stocks in soil and biomass due to LUC. For example, Bala *et al.*[40] find that "the climate effects of CO_2 storage in forests are offset by albedo changes at high latitudes, so that from a climate change mitigation perspective, projects promoting large-scale afforestation projects are likely to be counterproductive in these regions" (p. 6553). This suggests that the incorporation of these biogeophysical impacts into biofuel LCAs could significantly change the estimated CO_2e impact of biofuel policies.

The nitrogen cycle

Anthropogenic inputs of nitrogen to the environment, such as from the use of fertilizer or the combustion of fuels, can disturb aspects of the global nitrogen cycle, which ultimately have a wide range of environmental impacts, including eutrophication of lakes and coastal regions, fertilization of terrestrial ecosystems, acidification of soils and water bodies, changes in biodiversity, respiratory disease in humans, ozone damages to crops, and changes to global climate.[49–53] Galloway *et al.*[49] depict this as a "nitrogen cascade," in which "the same atom of Nr [reactive N, such as in NO_X or NH_Y] can cause multiple effects in the atmosphere, in terrestrial ecosystems, in freshwater and marine systems, and on human health" (p. 341; brackets added).

Nitrogen emissions to the atmosphere, as NO_X, NH_Y, or N_2O, can contribute to climate change through complex physical and chemical pathways that affect the concentration of ozone, methane, nitrous oxide, carbon dioxide, and aerosols:

(i) NO_X participates in a series of atmospheric chemical reactions involving CO, nonmethane hydrocarbons (NMHCs), H_2O, OH-, O_2, and other species that affect the production of tropospheric ozone, a powerful GHG[h] as well as an urban air pollutant.

(ii) In the atmospheric chemistry mentioned in (*i*), NO_X affects the production of the hydroxyl radical, OH, which oxidizes methane and thereby affects the lifetime of methane, another powerful GHG.

[h]According to the IPCC, the global mean radiative forcing due to changes in tropospheric ozone since 1750 is greater than the radiative forcing of all other gases and aerosols except carbon dioxide (CO_2) and methane (CH_4) (IPCC,[18] p. 204).

(iii) In the atmospheric chemistry mentioned in (*i*), NO_X affects the production of sulfate aerosol, which as an aerosol has, on the one hand, a net *negative* radiative forcing (and thereby a beneficial effect on climate)[18] but on the other hand adversely affects human health.

(iv) NH_Y and nitrate from NO_X deposit onto soils and oceans and then eventually re-emit N as N_2O, NO_X, or NH_Y. Nitrate deposition also affects soil emissions of CH_4.

(v) NH_Y and nitrate from NO_X fertilize terrestrial and marine ecosystems and thereby stimulate plant growth and sequester carbon in nitrogen-limited ecosystems.

(vi) NH_Y and nitrate from NO_X form ammonium nitrate, which as an aerosol has, on the one hand, a net *negative* radiative forcing[18] (and thereby a beneficial effect on climate) but on the other hand adversely affects human health.

(vii) As deposited nitrate, N from NO_X can increase acidity and harm plants and thereby reduce C–CO_2 sequestration.

Even though the development of many kinds of biofuels will lead to large emissions of NO_X, N_2O, and NH_Y, virtually all lifecycle analyses of CO_2e GHG emissions from biofuels ignore all N emissions and the associated climate effects except for the effect of N fertilizer on N_2O emissions. (Some preliminary, more comprehensive estimates are provided in Delucchi.[14,28]) Even in the broader literature on climate change there has been relatively little analysis of the climate impacts of N emissions, because as Fuglestvedt *et al.*[22] note, "GWPs for nitrogen oxides (NO_X) are amongst the most challenging and controversial" (p. 324). Shine *et al.*[54] estimate the global warming impacts of the effect of NO_X on O_3 and CH_4, focusing on regional differences (*i* and *ii* above); but they merely mention and do not quantify the effect of NO_X on nitrate aerosols (*vi* above), and do not mention the other impacts (~~*i–b*~~, *iv*, *v*, and *vii*). Prinn *et al.*[55] and Brakkee *et al.*[56] estimate effects ~~*1 and 2*.~~These studies, along with the preliminary work by Delucchi[14,28] suggest that the climate impacts of perturbations to the N cycle by the production and use of biofuels could be comparable to the impacts of LUC (discussed above).

Interactive and feedback effects between climate change, land use, and water use

Climate change can affect water use and land use. For example, changes in precipitation and evapotranspiration (due to climate change) will affect groundwater levels[57] and cropping patterns, which in turn will give rise to other environmental impacts, including feedback effects on climate change. People in less wealthy countries may be most vulnerable to these changes because they have less capacity to mitigate or adapt to impacts on groundwater.[57] These sorts of feedback interrelationships further complicate analyses of the impacts of biofuels on climate change, water use, and land use.

Summary of climate-change impacts

Nobody has yet done an analysis of the climate-change impacts of biofuels that uses a metric for the impacts of climate change that considers all of known or suspected potentially important climate-altering effects. As a result, we cannot yet make quantitative estimates of the climate impacts with confidence. However, we can make some useful qualitative statements. It is likely, for example, that biofuels produced from crops using current agricultural practices will *not* offer appreciable reductions in CO_2e climate impacts, and might even exacerbate climate change, compared with the impact of petroleum fuels. At the other end of the spectrum, we know that biofuels produced from true waste material (i.e., material with no alternative use) do not, by definition, affect agricultural practices or land uses, and hence will not significantly exacerbate climate change (unless the fuel-production process uses significant amounts of fossil fuels or fuel combustion produces non-CO_2 GHGs). Similarly, biofuels produced from cellulosic materials, such as grasses that are grown in the most ecologically sustainable manner possible are likely to cause less climate-change damage than do petroleum fuels.

With our current knowledge, however, it is difficult to asses the impact either of biofuels produced from crops using the *best*, most sustainable practices, or of biofuels produced from cellulosic materials using practices similar to those in conventional agriculture. In order to assess these production systems, and in general to provide more comprehensive assessments of the climate impacts of biofuels, we need improved, integrated lifecycle-/economic-/environmental-systems models, able to address the problems discussed here.

Water use and water quality

The production of biofuels can require orders of magnitude more water than does the production of petroleum fuels.[58–61] This high demand for water can stress water supplies and degrade water quality via salinization and pollution from agriculture and industry.[62,63] Unfortunately, there is no commonly used single metric that captures all relevant aspects of the impacts on water availability and water quality. Instead, most studies provide a relatively simple measure of water consumption or water use, or a measure of one specific impact on water quality, eutrophication. I discuss both of these measures (water use and eutrophication) here. In a separate section, I provide simple, original estimates of the water use of biofuel systems relative to some pertinent measures of water availability.

Impacts on water consumption and water use

Milà i Canals *et al.*[64] delineate a framework for treating impacts of freshwater use in LCA. They distinguish two kinds of water inputs to production systems, "blue" water (in groundwater) and "green" water (from rainfall), and two kinds of water outputs from production systems, nonevaporative uses (corresponding to water withdrawals or water use in other classifications) and evaporative uses (corresponding to water consumption in other classifications). Generally, water withdrawal is water removed from the ground or diverted from a surface-water source, and water consumption is equal to total withdrawals less the amount that is not available for reuse. Most estimates of the water use of biofuels, including the one presented here, are based on a similar classification.[59,60,65] (For further discussions of terms for water use and water resources, see Döll *et al.*,[66] FAO,[67] and Hutson *et al.*[68])

Measures of water usage, expressed in terms of volume of water per unit of biofuel energy output, are more meaningful when they are expressed relative to some measures of water availability. But even when expressed relative to water availability, measures of direct water use do not fully represent the impacts society cares about, because the measures still do not capture the costs of water supply, the costs of water treatment, adaptive responses, the possibility of water trade, the impacts of water pollution, and so on. However, it is possible to incorporate into a water-use metric a simplified treatment of one of the most important of these impacts, water pollution. I turn to this next.

Measuring impacts of water pollution

The production and use of biofuels can cause water pollution from fertilizer and pesticide runoff from crop fields and effluents from biofuel production facilities.[69] It is convenient to express the impacts of this pollution in terms of water use, because this then can be added to actual water usage to provide a broader index. The common way to do this is to estimate the amount of clean water that would be required to dilute polluted water to acceptable levels. For example, Dabrowski *et al.*[70] calculate the amount of water that would dilute non-point-source agrochemical water pollution to relevant water-quality guideline values, and express this hypothetical dilution requirement relative to total actual water use (irrigation water use plus rainfall) and to irrigation water use only, for five crops and five pollutants, for conditions in South Africa (Table 1).

Generally, pesticides require greater dilution than does phosphorus, which in turn requires greater dilution than does nitrogen. In round numbers, the amount of water required to dilute phosphorous pollution is of the same order of magnitude as the total direct water consumption (rainfall plus irrigation), for all crops, and is many times higher than the amount of water used for irrigation where irrigation is a small fraction of the total. In my estimates of water requirements, presented later, I include water needed to dilute pollution.

Eutrophication

A number of studies measure a specific impact of biofuel production on water quality, eutrophication. Increased concentrations of certain nutrients, particularly nitrogen and phosphorous, can promote excessive plant growth and decay in aquatic ecosystems, leading to increases in phytoplankton, decreases in dissolved oxygen, increased turbidity, loss of biodiversity, reductions in commercially important fish, increases in toxic plankton species, and other undesirable ecological effects.[69,71]

Table 1. **Amount of water that would dilute water pollution to acceptable levels, relative to actual water use, in South Africa**

	Maize		Wheat		Sugar cane		**Citrus**		**Cotton**	
Pollutant	Total[a]	Irrig.[b]	Total	Irrig.	Total	Irrig.	*Total*	*Irrig.*	*Total*	*Irrig.*
Nitrogen	0.5	11	0.3	0.9	0.3	3	0.2	0.7	0.05	0.09
Phosphorous	0.8	19	2	6	2	17	1.0	3	0.4	0.7
Endosulfan	–	–	–	–	–	–	2	5	2	4
Chlorpyrifos	–	–	–	–	–	–	9	23	15	28
Azinphosmethyl	–	–	–	–	–	–	2	5	2	4

Source: Table 8 in Dabrowski *et al.*[70]
[a]Irrigation water use plus rainfall; the numbers in these columns show dilution water as a fraction of total water use.
[b]Irrigation water use only; the numbers in these columns show dilution water as a fraction of irrigation water use.

To the extent that the production of biofuel feedstocks uses large amounts of nitrogen and phosphorous fertilizer, the runoff from production fields into water bodies can cause significant eutrophication.[69] To represent this, researchers typically estimate a phosphate-equivalent (sometimes nitrate-equivalent) "eutrophication potential" (analogous to the CO_2-equivalent global warming potential discussed above), calculated by multiplying nitrogen and phosphorous emissions by a "fate factor," which represents the fraction of the emitted pollutant that reaches the aquatic environment (this is 1.0 in the case of direct emission to water), and by an "effect factor," which represents the potential production of phytoplankton per gram of the pollutant relative to the potential production from a gram of phosphate[i] (PO_4).[72,73] Some researchers[72,74,75] also recognize that the impact of N and P inputs on eutrophication depends on whether the aquatic system is N-limited or P-limited or both, but it appears that no eutrophication potential index in widespread use has a sophisticated treatment of the effect of nutrient limitations on eutrophication.[j]

Several studies have applied eutrophication potentials to lifecycle analyses of biofuels.[4,7,76–79] Urban and Bakshi[76] find that a biomass-based fuel, 1,3-propanediol, has roughly twice the eutrophication potential (measured in kilogram PO_4 equivalent) as a fossil-fuel-based version of the fuel. Baral and Bakshi[4] find that the eutrophication potential (measured in kilogram PO_4 equivalent per vehicle miles of travel) of ethanol made from cellulosic materials is about 10 times that of gasoline. They conclude that "cellulosic ethanol may offer mixed benefits, reducing GHG potential while increasing eutrophication, acidification and human toxicity" (p. 3). UNEP[7] reports a comprehensive Swiss study that estimated that the eutrophication potential of ethanol from corn and biodiesel from soy are about five times that of petroleum, that the eutrophication potential of ethanol from wood is almost four times

[i]Other weighting/effect bases have been proposed. Kärrman and Jönsson[74] estimate weights in terms of grams of oxygen consumed per gram of nitrate, ammonium, or phosphorous in water, considering both the oxygen consumed to oxidize or degrade the pollutant directly ("primary" oxygen consumption), and the oxygen consumed to degrade the algae whose growth is stimulated by the availability of extra nutrients ("secondary" oxygen consumption). For example, for ammonium in P-limited aquatic systems, the overall nitrification reaction is $NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H^+ + H_2O$ and the weighting factor for primary oxygen consumption is 3.6 g-O_2/g-NH_4^+ The weighting factor for secondary oxygen consumption in this case is zero, because the extra ammonium does not stimulate algae growth in P-limited systems.

[j]Huijbregts and Seppälä[73] acknowledge the issue of nutrient limitation but do not formally account for it in their method of estimating eutrophication potential. Sleeswijk *et al.*[75] and Brentrup *et al.*[72] simply assume that freshwater systems are P-limited (and hence that N has no effect on eutrophication) and that marine systems are N-limited (and hence that P has no effect). Kärrman and Jönsson[74] estimate separate weighting factors for N-limited and P-limited aquatic ecosystems (see e.g., footnote *i*).

Table 2. **Land-use intensity of petroleum fuels and biofuels**

Fuel	Land-use intensity (km^2/TWh/yr)
Petroleum	45
Ethanol from corn	350
Ethanol from cellulose	460
Biodiesel from soy	890

Source: McDonald *et al.*[80]

higher, but that the potential of ethanol from grass is only about 1.3 times higher. Powers[77] finds that the use of fertilizer to grow corn (for ethanol) results in a eutrophication potential that exceeds proposed water quality standards. Although these studies use a relatively simple metric for eutrophication impact, as discussed above, they all indicate the production and use of biofuels can cause greater eutrophication than does the production and use of petroleum fuels.

Land use

Per unit of energy produced, biofuels require orders of magnitude more land than do petroleum fuels (Table 2).[80,81] The land requirement per unit of delivered biofuel can be calculated simply as the product of the yield (crop output per unit area), the production intensity (energy per unit crop), and a factor that accounts for the land-use impacts of any coproducts of the production process.[k] McDonald *et al.*[80] use this method to estimate the land-use intensity of different energy production techniques, and find that biofuels require roughly 100 to 200 times more land per unit of area than do fossil fuels in the year 2030 (Table 2).

McDonald *et al.*[80] estimate that biofuel crop production will occur mainly in temperate deciduous forests (55%), temperate grasslands (34%), and temperate conifer forests (9%).

It is more meaningful to express the land requirements of biofuel crop production relative to the availability of pertinent types of land. In the next section, I calculate the amount of land area required by biofuels relative to global arable land and global permanent pasture land. However, the land requirement for biofuel production, even expressed relative to some measure of available land, is just a rough indicator of other land-use impacts that society cares about, such as soil erosion, dust and smoke from agricultural activities, loss of habitat, biodiversity, and ecosystem services, and the effects of competition for land on the prices of commodities and services produced by land. I turn to these next.

Loss of habitat, biodiversity, and ecosystem services

The use of monocultural feedstocks (such as corn) to make biofuels can reduce biological diversity and the associated biocontrol services in agricultural landscapes.[7,9,82–84] The land-use intensity metric is not a good indicator of these impacts, in part because it does not reflect the impact of the land use on habitat integrity, wildlife corridors, and interactions at the "edges" of the affected area. Brentrup *et al.*[85] discuss a more direct indicator of the impacts of land use on habitat and biodiversity, the "Natural Degradation Potential" (NDP). The NDP measures how close land is to a pristine state: land untouched by humans (e.g., a wilderness) has an NDP of 0, land completely transformed by humans (e.g., a parking lot) has an NDP of 1.0, and land partially influenced by human activity (e.g., a managed grassland) has an NPD between 0 and 1. Koellner and Scholz[86] propose a similar measure of land-use impacts, the Ecosystem Damage Potential (EDP), based on the extent of the degradation of the "ecological quality" of the occupied land. Lindeijer[87] proposes free net primary biomass production as an indicator for the "life support" function of an ecosystem, and species number as an indicator of biodiversity. Milà i Canals *et al.*[88] suggest a variety of indicators for impacts on biodiversity (e.g., measures of species lost), biotic production potential (e.g, energy required to restore productive potential of the soil),

[k]Some biofuel production systems, such as corn-to-ethanol and soy-to-biodiesel, produce food and agricultural commodities as well as fuel. The marketing of these coproducts will displace other similar commodities from the market, and the land that would have been used to produce these displaced commodities will no longer be in production. This displacement effect on land use can be accounted for by a single multiplicative factor.

and soil quality (e.g., measures of soil erosion). (See also Lindeijer[89])

By any of these measures, biofuels made from crops can severely degrade natural habitats. To mitigate these effects, monocultures should be replaced by "natural, diversified and multifunctional vegetation that could meet the broad demand for goods and other resource functions in a sustainable fashion" (Kläy,[90] p. 25). See the section "Producing biomass energy feedstocks with lower impacts on climate change, water use, water quality, and land use" for further discussion.

Soil erosion

Biofuel-crop harvesting practices can affect soil erosion and the nutrient and organic content of the soil, which in turn can affect the use of fertilizer.[9] For example, if crop residues are removed from the field and used as a source of energy in the production of a biofuel, then soil erosion might increase and fewer nutrients and less organic matter might be returned to the soil.[37,77,91,92;l] Additional fertilizer may be required to balance any loss, and the use of additional fertilizer will result in additional environmental impacts. Again, a land-use intensity index gives a sense only of the potential scale of the problems.

Effects of competition for land on prices of commodities and services produced by land

As Rajagopal and Zilberman[11] note, "allocating land for biofuels means taking land away from other uses like food or environmental preservation" (p. 70). Economic theory and economic models tell us that a demand-driven increase in the price of a biofuel feedstock, such as corn (for corn–ethanol), will benefit the producers of the feedstock but cost those who consume the feedstock directly or use it as a factor of production.[96,97] In many if not most cases, the people who benefit tend to be wealthy, and the people who lose tend to be poor.[98] For example, Rajagopal *et al.*[99] analyze the distributional welfare impacts of support for corn ethanol in the United States, and conclude that support for ethanol benefits gasoline consumers and corn producers and harms food consumers and oil producers. They conclude that a consequence of support for biofuels is "that the poor go hungry so the wealthy can drive bigger cars farther" (p. 5).

Similarly, Ewing and Msangi[100] assess trade-offs between biofuel production and food security in developing countries, and conclude that biofuel production can generate additional income in the agricultural sector, but that these benefits may accrue mainly to large-scale commercial producers (as opposed to small, local producers) and that the new wealth may not be distributed widely enough to offset the impacts on the poor of higher food prices. For these reasons, Vanwey[98] concludes that "in the developing world, the impacts [of large-scale biofuel production] will be virtually uniformly negative" (p. 211; brackets added). Phalan[101] comes to a similar conclusion regarding biofuels in Asia.

It is clear, then, that a main effect of the competition for land between biofuel crops and food crops will be higher food prices, which will hit the poor particularly hard. Indeed, if the competition between biofuel crop production and food crop production is extensive and severe enough, it is possible that the consequent increases in agricultural prices will cause some people to go hungry and even starve.[102]

Finally, as higher prices for biofuels make certain kinds of land more valuable, people may fight over land—a fight, which poor land holders inevitably lose.[103] (I note that there is some irony here, because biofuels are being promoted not only as environmentally friendly, but also as a more secure, less geopolitically fractious alternative to petroleum.) As Kläy[90] observes:

> The need to absorb and suppress carbon as a consequence of climate change is creating a new interest in resource use among economically and politically powerful actors. These new "users" appear in rural areas, usually in marginal regions, and make demands on the same economically devalued resources as indigenous populations, who are often among the poorest

[l]There may be similar consequences from harvesting whole trees in short-rotation, intensive-cultivation (SRIC) system used to produce cellulosic feedstocks for ethanol production.[93–95] Chatarpaul *et al.*[95] conclude that the effects of whole tree harvesting will vary from site to site, and that "sufficient evidence is currently available regarding the detrimental effects of excess residue removal to urge a cautious, experimental approach in applying whole tree harvesting" (p. 124).

> people in the world. . .[thus] new demands on [biomass] resources are being made by centralised institutions on behalf of economically powerful groups, in areas where the earth's poorest people have barely been able to eke out a living (p. 25).

Example calculations of the land and water requirements

In order to put the discussion of water and land impacts into a realistic context, I estimate the impacts of developing the biofuels program that is part of a recent comprehensive set of global energy projections by the International Energy Agency (IEA).[104] The IEA scenarios include detailed assumptions about technology and energy uses for power, transportation, and end-use. Here, I analyze the IEA's "Baseline" and "Blue MAP" scenarios. The average economic growth amounts to 3.3% per year in both scenarios, but the energy technology mix is radically different: in the "Blue MAP" scenario there is much greater use of biofuels and other forms of renewable energy. For example, in the "Blue MAP" scenario biofuels provide 27% of total ground transportation energy in the world, versus only 3% in the "Baseline" scenario.

With estimates of the land and water requirements per unit of biofuel-cellulosic feedstock produced (including water needed to dilute pollution),[59,65,105,106] and of total available land and freshwater,[67,107,108,109] one can make rough estimates of the land and water requirements of the biofuel consumption levels projected by the IEA in its "BLUE Map 2050" scenario, relative to available global resources. The IEA "BLUE Map 2050" case, which has the highest level of biofuel consumption out of all the IEA scenarios, requires:

- 6% of current global permanent pasture land;
- 16% of current global arable land;
- 6% of global renewable freshwater;
- 117% of current global water use by agriculture; and
- 82% of current total global water use.

It is interesting to express the land and water requirements relative to the percent of energy demand satisfied by biofuels. For every 10% of the IEA-projected *global* ground transportation energy demand satisfied by cellulosic biofuels, the land and water requirements are:[m]

- 2% of current global permanent pasture land;
- 6% of current global arable land;
- 2% of global renewable freshwater;
- 44% of current global water use by agriculture; and
- 31% of current total global water use.

These calculations assume the use of "second-generation" cellulosic biofuels. As shown in Table 3, the water use of "first generation" biofuels, ethanol from irrigated corn or biodiesel from irrigated soy, is somewhat higher than the water use of cellulosic biofuels. Replacing 10% of gasoline or diesel fuel with biofuels from irrigated corn or soybeans would require roughly 100% of total U.S. freshwater consumption, when water required to dilute pollution is included.

By comparison, Fraiture *et al.*[112] use the WATERSIM model to estimate that supplying 5% of U.S. gasoline energy with corn–ethanol would require 9% of the total cropped area in the United States and 20% of U.S. irrigation withdrawals. They also estimate that supplying 7.5% of the world's gasoline energy with biofuels would require 3% of global cropped area and 4% of total global irrigation withdrawals.

Note that all of these percentages (for the world cellulosic case shown above, and the U.S. crop-based biofuels case in Table 3) are with respect to the current situation, and hence do not reflect increases in demand for land and water in other sectors, particularly agriculture. Studies project that total global water withdrawals could increase by more than 20% by 2025, leading to severe water stresses in several regions of the world.[113] In the longer term, the number of people living in regions experiencing high stresses on water supplies (defined here as less than 1000 m^3/capita/year) could increase by several billion, with most of the increases occurring in China, India, West Asia, and North Africa.[62,114] However, even if future freshwater withdrawals for all uses other than biofuel feedstock production were to double by 2050, the addition of the water demand

[m] See the Royal Society[84] for a similar calculation of the percent of arable land in the United Kingdom needed to supply 5% of transport energy with biofuels.

Table 3. **Water requirements of replacing 10% of gasoline or diesel fuel with biofuels from irrigated crops in the United States**

	Irrigated corn ethanol replaces 10% of gasoline		Irrigated soy biodiesel replaces 10% of diesel	
	Pollution not diluted	Pollution diluted	Pollution not diluted	Pollution diluted
Percent of total U.S. water withdrawal	14% (3% to 36%)	28% (6% to 72%)	20% (6% to 34%)	40% (12% to 68%)
Percent of total U.S. freshwater consumption	35% (7% to 98%)	70% (14% to 196%)	52% (15% to 92%)	104% (30% to 184%)

Source: My calculations, based on biofuel water-use estimates in the U.S. Department of Energy,[61] gasoline and diesel fuel data in Davis *et al.*,[110] U.S. water withdrawal estimates in Hutson *et al.*,[68] and U.S. freshwater consumption estimates in Solley *et al.*[111] The table shows the average percentage, and the low-to-high percentages in parentheses, based on low, average, and high estimates of biofuel water use. Water consumption is equal to total withdrawals less the amount that is not available for reuse. On the basis of the estimates of Table 2, I have assumed that the amount of water needed to dilute pollution is equal to the amount actually consumed.

estimated for the IEA "BLUE Map 2050" scenario still would result in a total water withdrawal of just under 20% of the total global renewable freshwater resource. Alcamo and Henrichs[115] assume that when withdrawals are less than 20% of the available resource, there is low stress on water resources.

Thus, even though the land and water requirements of biofuels are very large with respect to the requirements of current transportation energy systems, on the one hand, and large with respect to the requirements of current agricultural systems, on the other, at the *global* level there will be no obvious water and (pasture) land resource constraint on the development of bioenergy for several decades, unless the requirements of other sectors have been vastly underestimated. (Müller *et al.*[116] come to the same conclusion.)

However, water and arable land are not distributed uniformly across the globe with respect to population or energy demand, and as a result at the regional level there can be severe constraints on land and water availability. In parts of China[n], South Asia,[o] West Asia, and Africa current demands are already stressing water supplies, and these stresses are expected to increase dramatically in the coming decades.[63,113,–115,119,120] The development of biofuel feedstocks in these areas could place intolerable stresses on water supplies.[112,116,121] Even in the United States, a major expansion of biofuel production could seriously exacerbate water-quantity and water-quality problems.[122]

However, if biofuels can be traded globally, the way petroleum fuels are today, then regional constraints on land and water need not impede the development of biofuels. FAO data (http://faostat.fao.org/faostat/) and the analysis of Berndes[65] indicate that there are large regions of the world with ample land and water to produce biofuels: large parts of North America and South America, Russia, Indonesia, and parts of sub-Saharan Africa. If biofuel feedstocks can be grown in these resource-rich regions at reasonable cost and with minimal environmental impact, and if future demands for

[n]Yang *et al.*[117] estimate the water requirements and land requirements of producing biofuels in China. They conclude that "given the extremely small per capita arable land in China, it is very difficult to spare this amount of land from currently cultivated land for feedstocks. The associated water requirement further lowers the possibility because much of the northern land already endures serious water shortage" (p. 1884).

[o]To reduce the adverse impacts of biofuels on land use and water use, India is promoting the development of Jatropha, a drought tolerant crop that can be grown on marginal lands.[118]

land and water by other sectors do not dramatically exceed present expectations, then arguably biofuel production need not be constrained by the global availability of land and freshwater. (See also Berndes[65] for a more detailed but similar analysis and conclusion.)

Producing biomass energy feedstocks with lower impacts on climate change, water use, water quality, and land use

The environmental impacts of producing bioenergy feedstocks can be reduced by mixing plant species, reducing energy and chemical inputs, managing material flows to achieve nearly a closed system, and targeting biofuel crop production to degraded or abandoned lands.[9,38,90,123–129] Reijnders[124] suggests that "sustainable" production of biofuel feedstocks requires that there be no net depletion of soil and water, no increase in chemical and nutrient contents in soils, and no net increase in emissions of organic and N compounds to the atmosphere. He concludes that "to maintain ecosystem services of nature useful to mankind, restriction of biomass production to degraded and currently fallow land is to be preferred" (p. 863).

Jørgensen *et al.*[123] describe a "Combined Food and Energy" (CFE) system "which has achieved a fossil fuel energy-neutral cropping system and biodiversity and microclimate benefits by intercropping perennial energy crops (willow, alder, and hazel) with annually rotated crops"(p. 243). This suggests that a CFE program with organically grown crops can protect water quality because the production of short-rotation energy crops reduces nitrate leaching to low levels.

Tilman *et al.*[38] propose that low-input, high-diversity (LIHD) mixtures of native grassland perennials in the United States can provide more biodiverse habitat and even higher yields than can monocultural perennials, at least on relatively infertile soils. They suggest that LIHD systems can be grown successfully on abandoned, degraded agricultural lands, and actually improve the quality of soil and water on such lands. (However, I note that this improvement is relative to leaving the land degraded, not relative to restoring the land to its most environmentally beneficial use.)

Finally, Lehmann *et al.*[126] and Mathews[127] discuss the possibility of converting a portion of biomass to a charcoal-like compound known as "biochar" that is returned to the soil while the rest of the biomass is converted into energy products. Here, low-temperature pyrolysis converts some of the carbon in biomass into a carbon-dense, stable, nondecomposing compound (biochar) that can be added to soil and effectively sequesters carbon in the ground for at least hundreds of years. Biochar also improves the fertility of the soil and reduces emissions of other greenhouse gases, such as N_2O.

However, it is not clear that such bioenergy systems can be sustainable and commercially viable at large scales. For example, Johansson and Azar[130] suggest that it is unlikely that commercial bioenergy farmers will *choose* to grow bioenergy crops on degraded land, as it is likely to be relatively unprofitable. Muller[128] concludes that production of bioenergy from waste materials can be sustainable, but that large-scale production of bioenergy probably cannot satisfy all of the requirements of sustainability. Similarly, Sala *et al.*[82] note that while some small-scale biofuel production systems can maintain high biodiversity, "it is unlikely that solutions that produce biofuels while maintaining biodiversity can be implemented at the scale necessary to meet current biofuel demand" (p. 131).

Conclusions

Research over the past two decades has helped us understand many aspects of the impacts of biofuel development on climate change, water use, and land use. However, because of the complexity of the ecological, economic, and technological systems that affect climate change, land use, and water use, and the difficulty of constructing useful metrics of impacts, there are as yet no definitive quantitative assessments that capture all of the aspects of climate change, water use, and land use that we care about.[p]

[p]There have been some interesting attempts to develop an aggregate metric covering a range of impacts, as opposed to a comprehensive metric in each impact category. Scharlemann and Laurance[131] discuss a Swiss study that expresses disparate environmental impacts of biofuels, including natural resource depletion and damages to human health and ecosystems, by a single indicator. The Swiss study finds the total environmental impact of the major commercial biofuels, including corn ethanol, sugarcane ethanol, and soy biodiesel, exceeds that of gasoline,

Nevertheless, we are able to make some qualitative overall assessments. It is likely that biofuels produced from crops (e.g., ethanol from corn) using conventional agricultural practices, will *not* mitigate the impacts of climate change, and will exacerbate stresses on water supplies, water quality, and land use, compared with petroleum fuels. As Phalan[101] puts it, "if risks and uncertainties are inadequately assessed and managed, even the best biofuels have the potential to damage the poor, the climate and biodiversity" (p. S28). To avoid these problems, biofuel feedstocks will have to be grown on land that has no alternative commercial use[q] and no potential alternative ecological benefits, in areas with ample rainfall or groundwater, and with little or no inputs of fertilizers, chemicals, and fossil fuels. Although this can be done experimentally at small scales, it is not clear that it can be done economically and sustainably at large scales. We can conclude, then, that the development of sustainable biofuels depends not only on technological progress in growing feedstocks and producing fuels, but also on developing the policies, regulations, and incentives that direct commercial biofuel development in socially and environmentally beneficial ways.

in some cases (e.g., for corn ethanol) by more than a factor of two. Baral and Bakshi,[4,132,133] Hau and Bakshi,[134] and Urban and Bakshi[76] develop an Energy Consumption index, which accounts for a wide range of resources in the evaluation of biofuels. Baral and Bakshi[132] conclude that ~~"Large scale substitution of biofuels [corn ethanol and soy biodiesel] for petroleum-based fuels consume disproportionate amounts of land, soil, water and other natural capital that prevent them from being used in other critical sectors. This poses a severe constraint for large scale substitutions on physical and economic grounds" (p. 14; brackets added);~~ See Clift[135] for a general discussion of metrics for assessing technological, economic, ecological, and social aspects of sustainable development, and (S&T)[2] Consultants[12] and von Blottnitz and Curran[13] for a discussion of metrics used in biofuel LCA.

[q]If the land has an alternative commercial use, say for agriculture or forestry, then the displacement of those alternative uses by biofuel production will lead, eventually, to the cultivation or development of land that otherwise would not have been cultivated or developed, and this new cultivation or development will tend to adversely impact climate change, water use, and land use.

Acknowledgments

I thank Deepak Rajagopal, Richard Plevin, Alissa Kendall, Gouri Shankar Mishra and a reviewer for providing helpful comments. I alone am responsible for this work.

Conflicts of interest

The author declares no conflicts of interest.

References

1. Thornley, P., P. Upham, Y. Huang, *et al.* 2009. Integrated assessment of bioelectricity options. *Energy Policy* **37:** 890–903.
2. Schmer, M.R., K.P. Vogel, R.B. Mitchell & R.K. Perrin. 2008. Net energy of cellulosic ethanol from switchgrass. *Proc. Natl. Acad. Sci. USA* **105:** 464–469.
3. Hammerschlag, R. 2006. Ethanol's energy return on investment: a survey of the literature 1990 – present. *Environ. Sci. Technol.* **40:** 1744–1750.
4. Baral, A. & B.R. Bakshi. 2008. *Life Cycle Assessment of the Production and Use of Ethanol from Cellulose*. Draft report prepared for the U.S. Environmental Protection Agency. Department of Chemical and Biomolecular Engineering, Ohio State University. Ohio, OH. November 30.
5. Granda, C.B., L. Zhu & M.T. Holtzapple. 2007. Sustainable liquid biofuels and their environmenal impact. *Environ. Progress* **26:** 233–250.
6. MacLean, H.L. & S. Spatari. 2009. The contribution of enzymes and process chemicals to the life cycle of ethanol. *Environ. Res. Lett.* **4:** doi:10.1088/1748–9326/4/1/014001. Q3
7. United Nations Environment Programme, Working Group on Biofuels of the International Panel for Sustainable Resource Management. 2009. *Towards Sustainable Production and Use of Resources: Assessing Biofuels*. www.unep.fr/scp/rpanel/pdf/Assessing˙Biofuels˙Full˙Report.pdf Q4
8. Menichetti, E. & M. Otto. 2009. Energy balance and greenhouse gas emissions of biofuels from a lifecycle perspective. In *Biofuels: Environmental Consequences and Interactions with Changing Land Use*. R. Howarth & S. Bringezu, Eds.: 81–109. Cornell University. Ithaca, NY. Available at: http://cip.cornell.edu/biofuels/.
9. Reijnders, L. & M.A.J. Huijbregts. 2009. *Biofuels for Road Transport, a Seed to Wheel Perspective*. Green Energy and Technology Series. Springer-Verlag. London, UK.

10. Börjesson, P. 2009. Good or bad bioethanol from a greenhouse perspective – what determines this? *Appl. Energy* **86:** 589–594.
11. Rajagopal, D. & D. Zilberman. 2008. Environmental, economic, and policy aspects of biofuels. *Found. Trends Microecon.* **4:** 353–468.
12. (S&T)^2 Consultants Inc., Cheminfo Services Inc., H. MacLean & Fugacity Technology Consulting. 2008. *Sensitivity Analysis of Bioethanol LCA Models to Determine Assumptions with the Greatest Influence on Outputs*, March 31. www.ghgenius.ca/reports/BioethanolLCAFinalReport.pdf. Q5
13. von Blottnitz, H. & M.A. Curran. 2007. A review of assessments conducted on bio-ethanol as transportation fuel from a net energy, greenhouse-gas, and environmental life cycle perspective. *J. Cleaner Prod.* **15:** 607–619.
14. Delucchi, M.A. 2006. *Lifecycle Analysis of Biofuels*. UCD-ITS-RR-06–08, Institute of Transportation Studies, University of California. Davis, CA. May. www.its.ucdavis/people/faculty/delucchi.
15. Fleming, J.S., S. Habibi & H.L. MacLean. 2006. Investigating the sustainability of lignocellulosic-derived fuels for light-duty vehicles. *Transp. Res. D* **11:** 146–159.
16. Farrell, A.E., R.J. Plevin, B.T. Turner, *et al.* 2006. Ethanol can contribute to energy and environmental goals. *Science* **311:** 506–508.
17. International Energy Agency. 2004. *Biofuels for Transport*. Organization for Economic Cooperation and Development. Paris. April. www.iea.org/books.
18. Intergovernmental Panel on Climate Change. 2007. *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the IPCC. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor & H.L. Miller. Cambridge University Press. Cambridge, UK. www.ipcc.ch/ipccreports/ar4-wg1.htm.
19. Friedlingstein, P. & S. Solomon. 2005. Contributions of past and present human generations to committed warming caused by carbon dioxide. *Proc. Natl. Acad. Sci. USA* **102:** 10832–10836.
20. Meehl, G.A., *et al*. 2005. Climate change projections for the twenty-first century and climate change commitment in the CCSM3. *J. Clim.* **19:** 2597–2616.
21. Meehl, G.A., W.M. Washington, W.D. Collins, *et al.* 2005. How much more global warming and sea level rise. *Science* **307:** 1769–1772.
22. Fuglestvedt, J.S., T.K. Bernsten, O. Godal, *et al*. 2003. Metrics of climate change: assessing radiative forcing and emission indices. *Clim. Change* **58:** 267–331.
23. O'Neill, B.C.. 2003. Economics, natural science, and the costs of global warming potentials. *Clim. Change* **58:** 251–260.
24. Godal, O. 2003. The IPCC's assessment of multidisciplinary issues: the case of greenhouse gas indices. *Clim. Change* **58:** 243–249.
25. Bradford, D.F. 2001. Time, money, and tradeoffs. *Nature* **410:** 649–650.
26. Reilly, R., M. Babiker, & M. Mayer. 2001. *Comparing Greenhouse Gases*. Report No. 77, MIT Joint Program on the Science and Policy of Global Change, Massachusetts Institute of Technology. Cambridge, MA. July. Available at: http://globalchange.mit.edu/files/document/MITJPSPGC˙Rpt77.pdf.
27. Manne, S. & R.G. Richels. 2001. An alternative approach to establishing tradeoffs among greenhouse gases. *Nature* **410:** 675–677.
28. Delucchi, M.A., *et al*. 2003. *A Lifecycle Emissions Model (LEM): Lifecycle Emissions from Transportation Fuels, Motor Vehicles, Transportation Modes, Electricity Use, Heating and Cooking Fuels, and Materials*. UCD-ITS-RR-03–17, Institute of Transportation Studies, University of California. Davis, CA. December. www.its.ucdavis/people/faculty/delucchi.
29. Kendall, A. & B. Chang. 2009. Estimating life cycle greenhouse gas emissions from corn-ethanol: a critical review of U.S. practices. *J. Cleaner Prod.* **17:** 1175–1182.
30. Intergovernmental Panel on Climate Change. 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara & K. Tanabe. Prepared by the National Greenhouse Gas Inventories Programme, published by the Institute for Global Environmental Strategies. Japan. www.ipcc-nggip.iges.or.jp/public/2006gl/index.htm.
31. Adler, P.R., S.J. Del Grosso & W.J. Parton. 2007. Lifecycle assessment of net greenhouse-gas flux for bioenergy cropping systems. *Ecol. Appl.* **17:** 675–691.
32. Crutzen, P.J., A.R. Mosier, K.A. Smith & W. Winiwarter. 2008. N_2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. *Atmos. Chem. Phys.* **8:** 389–395.
33. Davidson, E.A. 2009. The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860. *Nat. Geosci.* **2:** 659–662.
34. Delucchi, M.A. ~~2009.~~ A conceptual framework for estimating bioenergy-related land-use change and its impacts over time. ~~Submitted to~~ *Biomass Bioenergy*. Q6
35. Searchinger, T., R. Heimlich, R.A. Houghton, *et al.* 2008. Use of U.S. croplands for biofuels increases

greenhouse gases through emissions from land use change. *Science* **319:** 1238–1240.
36. Fargione, J., J. Hill, D. Tilman, *et al.* 2008. Land clearing and the biofuel carbon debt. *Science* **319:** 1235–1238.
37. Lal, R. 2005. World crop residues production and implications of its use as a biofuel. *Environ. Int.* **31:** ~~585~~–584.
38. Tilman, D., J. Hill & C. Lehman. 2006. Carbon-negative biofuels from low-input high-diversity grassland biomass. *Science* **314:** 1598–1600.
39. Righelato, R. & D.V. Spracklen. 2007. Carbon mitigation by biofuels or by saving and restoring forests?. *Science* **317:** 902.
40. Bala, G., K. Caldeira, M. Wickett, *et al.* 2007. Combined climate and carbon-cycle effects of large-scale deforestation. *Proc. Natl. Acad. Sci. USA* **104:** 6550–6555.
41. Feddema, J.J., K.W. Oleson, G.B. Bonan, *et al.* 2005. The importance of land-cover change in simulating future climates. *Science* **310:** 1674–1678.
42. Pyke, C.R. & S.J. Andelman. 2007. Land use and land cover tools for climate adaptation. *Clim. Change* **80:** 239–251.
43. Notaro, M., S. Vavrus & Z. Liu. 2007. Global vegetation and climate change due to future increases in CO_2 as projected by a fully coupled model with dynamic vegetation. *J. Clim.* **20:** 70–90.
44. Marland, G., *et al.* 2003. The climatic impacts of land surface change and carbon management, and the implications for climate-change mitigation policy. *Clim. Policy* **3:** 149–157.
45. Lamptey, B.L., E.J. Barron & D. Pollard. 2005. Impacts of agriculture and urbanization on the climate of the northeastern United States. *Glob. Planet. Change* **49:** 203–221.
46. Lobell, D.B., G. Bala & P.B. Duffy. 2006. Biogeophysical impacts of cropland management changes on climate. *Geophys. Res. Lett.* **33:** L06708.
47. ~~Jacobson, M.Z. 2007. The effects of agriculture on climate and air pollution in California. Submitted to *J. Appl. Meteorol. Clim.*, February 5. www.stanford.edu/group/efmh/jacobson/IrrigPap1206.pdf.~~
48. Georgescu, M., D.B. Lobell & C.B. Field. 2009. Potential impact of U.S. biofuels on regional climate. *Geophys. Res. Lett.* **36:** L21806, doi:10.1029/2009GL040477.
49. Galloway, J.N., J.D. Aber, J.W. Erisman, *et al.* 2003. The nitrogen cascade. *BioScience* **53:** 341–356.
50. Mosier, A.R., M.A. Bleken, P. Chaiwanakupt, *et al.* 2002. Policy implications of human-accelerated nitrogen cycling. *Biogeochemistry* **57/58:** 477–516.
51. Jenkinson, D.W. 2001. The impact of humans on the nitrogen cycle, with focus on temperate arable agriculture. *Plant Soil* **228:** 3–15.
52. Galloway, J.N. 1998. The global nitrogen cycle: changes and consequences. *Environ. Poll.* **102**(Suppl. 1): 15–24.
53. Vitousek, P.M., J.D. Aber, R.W. Howarth, *et al.* 1997. Technical report: human alteration of the global nitrogen cycle: sources and consequences. *Ecol. Appl.* **7:** 737–750.
54. Shine, K.P., T.K. Bernsten, J.S. Fuglesttvedt & R. Sausen. 2005. Scientific issues in the design of metrics for inclusion of oxides of nitrogen in global climate agreements. *Proc. Natl. Acad. Sci. USA* **102:** 15768–15773.
55. Prinn, R.G., J. Reilly, M. Sarofim, *et al.* 2005. *Effects of Air Pollution Control on Climate.* Report No. 118, MIT Joint Program on the Science and Policy of Global Change. Cambridge, MA. January. Available at: http://web.mit.edu/globalchange/www/MITJPSPGC˙Rpt118.pdf.
56. Brakkee, K.W., M.A.J. Huijbregts, B. Eickhout, *et al.* 2008. Characterisation factors for greenhouse gases at a midpoint level including indirect effects based on calculations with the IMAGE model. *Int. J. Lifecycle Anal.* **13:** 191–201.
57. Bovolo, C.I., G. Parkin & M.Sophocleous. 2009. Groundwater resources, climate, and vulnerability. *Environ. Res. Lett.* **4:** 035001.
58. Rio Carillio, A.M. & C. Frei. 2009. Water: a key resource in energy production. *Energy Policy* **37:** 4303–4312.
59. Gerbens-Leenes, P.W., A.Y. Hoekstra & Th. Van Der Meer. 2009. The water footprint of energy from biomass: a quantitative assessment and consequences of an increasing share of bio-energy in energy supply. *Ecol. Econ.* **68:** 1052–1060.
60. King, C.W. & M.E. Webber. 2008. Water intensity of transportation. *Environ. Sci. Technol.* **42:** 7866–7872.
61. U.S. Department of Energy. 2006. *Energy Demands on Water Resources.* Report to Congress on the Interdependency of Energy and Water. December. www.sandia.gov/energy-water/congress˙report.htm.
62. Zimmerman, J.B., J.R. Mihelcic & J. Smith. 2008. Global stressors on water quality and quantity. *Environ. Sci. Technol.* **42:** 4247–4254.
63. Shah, T., D. Molden, R. Sakthivadivel & D. Seckler. 2000. *The Global Groundwater Situation Overview of Opportunities and Challenges.* International Water Management Institute. Colombo, Sri Lanka. Available at: http://www.lk.iwmi.org/pubs/WWVisn/GrWater.pdf.
64. Milà i Canals, L., J. Chenoweth, A. Chapagain, *et al.* 2009. Assessing freshwater use impacts in LCA: Part I – inventory modelling and characterisation factors for

main impact pathway. *Int. J. Lifecycle Assess.* **14:** 28–42.

65. Berndes, G. 2002. Bioenergy and water – the implications of large-scale bioenergy production for water use and supply. *Global Environ. Change* **12:** 253–271.
66. Döll, P., F. Kaspar & B. Lehner. 2003. A global hydrological model for deriving water availability indicators: model tuning and validation. *J. Hydrol.* **270:** 105–134.
67. Food and Agriculture Organization of the United Nations. 2003. *Review of Water Resources By Country.* Land and Water Development Division, FAO-UN. Rome. ftp://ftp.fao.org/agl/aglw/docs/wr23e.pdf.
68. Hutson, S.S., N.L. Barber, J.F. Kenny, *et al.* 2004. *Estimated Use of Water in the United States in 2000.* U.S. Geological Survey Circular 1268, U.S. Geological Survey. Reston, VA. Available at: http://pubs.usgs.gov/circ/2004/circ1268/.
69. Simpson, T.W., L.A. Martinelli, A.N. Sharpley & R.W. Howarth. 2009. Impact of ethanol production on nutrient cycles and water quality: The United States and Brazil as case studies. In *Biofuels: Environmental Consequences and Interactions with Changing Land Use.* R. Howarth & S. Bringezu, Eds: 153–167. Cornell University. Ithaca, NY. Available at: http://cip.cornell.edu/biofuels/.
70. Dabrowski, J.M., K. Murray, P.J. Ashton & J.J. Leaner. 2009. Agricultural impacts on water quality and implications for virtual water trading decisions. *Ecol. Econ.* **68:** 1074–1082.
71. Smith, V.H., G.D. Tilman & J.C. Nekola. 1999. Eutrophication: impacts of excess nutrient inputs on freshwater, marine, and terrestrial ecosystems. *Environ. Pollut.* **100:** 179–196.
72. Brentrup, F., J. Küsters, H. Kuhlmann & J. Lammel. 2004. Environmental impact assessment of agricultural production systems using the life cycle assessment methodology I. Theoretical concept of a LCA method tailored to crop production. *Eur. J. Agronomy* **6:** 339–348.
73. Huijbregts, M.A.J. & J. Seppälä. 2001. Life cycle impact assessment of pollutants causing aquatic eutrophication. *Int. J. Life Cycle Assess.* **6:** 339–343.
74. Kärrman, E. & H. Jönsson. 2001. Including oxidisation of ammonia in the eutrophication impact category. *Int. J. Lifecycle Assess.* **6:** 29–33.
75. Sleeswijk, A.W., L.F.C.M. van Oers, J.B. Guinée, *et al.* 2007. Normalisation in product life cycle assessment: an LCA of the global and European economic systems in the year 2000. *Sci. Total Environ.* **390:** 227–240.
76. Urban, R.A. & B.R. Bakshi. 2009. 1, 3-propanediol from fossils versus biomass: a life cycle evaluation of emissions and ecological resources. *Ind. Eng. Chem. Res.* **48:** 8068–8082.
77. Powers, S.E. 2005. *Quantifying Cradle-to-Farm Gate Life-Cycle Impacts Associated with Fertilizer Used for Corn, Soybean, and Stover Production.* NREL/TP-510-37500, National Renewable Energy Laboratory. Golden, CO. May. www1.eere.energy.gov/biomass/pdfs/37500.pdf.
78. Heller, M.C., G.A. Keoleian & T.A. Volk. 2003. Life cycle assessment of a Willow bioenergy cropping system. *Biomass Bioenergy* **25:** 147–165.
79. Kadam, K.L. 2002. Environmental benefits on a life cycle basis of using bagasse-derived ethanol as a gasoline oxygenate in India. *Energy Policy* **30:** 371–384.
80. McDonald, R.I., J. Fargione, J. Klesecker, *et al.* 2009. Energy sprawl or energy efficiency: climate policy impacts on natural habitat for the United States of American. *PLoS ONE* **4:**e6802. doi:10.1371/journal.pone.0006802. Q14
81. California Air Resources Board. 2009. *Proposed Regulation to Implement the Low Carbon Fuel Standard.* Volume 1, Staff Report: Initital Statement of Reasons. Stationary Source Division. Sacramento, CA. March. www.arb.ca.gov/regact/2009/lcfs09/lcfs09.htm.
82. Sala, O.E., D. Sax & H. Leslie. 2009. Biodiversity consequences of increased biofuel production. In *Biofuels: Environmental Consequences and Interactions with Changing Land Use.* R. Howarth & S. Bringezu, Eds.: 127–137. Cornell University. Ithaca, NY. Available at: http://cip.cornell.edu/biofuels/.
83. Landis, D.A., M.M. Gardiner, W. Van Der Werf & S.M. Swinton. 2008. Increasing corn for biofuel production reduces biocontrol services in agricultural landscapes. *Proc. Natl. Acad. Sci. USA* **105:** 20552–20557.
84. The Royal Society. 2008. *Sustainable Biofuels: Prospects and Challenges.* Policy Document 01/08. The Royal Society. London, UK. Available at: http://royalsociety.org/Sustainable-biofuels-prospects-and-challenges/.
85. Brentrup, F.J., Küsters, J. Lammel & H. Kuhlmann. 2002. Life cycle impact assessment of land use based on the Hemeroby concept. *Int. J. Life Cycle Assess.* **20:** 247–264. Q15
86. Koellner, T. & W. Scholz. 2007. Assessment of land use impacts on the natural environment, part 1: an analytical framework for pure land occupation and land use change. *Int. J. Life Cycle Assess.* **12:** 16–33.
87. Lindeijer, E. 2000. Biodiversity and life support impacts of land use in LCA. *J. Cleaner Prod.* **8:** 313–319.

88. Milà i Canals, L., C. Bauer, J. Depestele, *et al*. 2006. Key elements in framework for land use impact assessment within LCA. *Int. J. Life Cycle Assess.* **12:** 5–15.

89. Lindeijer, E. 2000. Review of land use impact methodologies. *J. Cleaner Prod.* **8:** 273–281.

90. Kläy, A. 2000. *The Kyoto Protocol and the Carbon Debate*. Development and Environment Report No. 18, Center for Development and Environment, University of Berne, Berne, Switzerland. www.cde.unibe.ch/info/pdf/waldco2.pdf.

Q16 91. Pimentel, D. & R. Lal. 2007. Biofuels and the environment. *Science* **317:** 897.

92. Wilhelm, W.W., J.M.F. Johnson, J.L. Hatfield, *et al*. 2004. Crop and soil productivity response to corn residue removal: a literature review. *Agronomy J.* **96:** 1–17.

93. Hendrickson, O.Q., J.B. Robinson & D.B. Rachar. 1984. Effects of two harvesting methods on biological and chemical properties of forest soil. In *Fifth Canadian Bioenergy R & D Seminar*. S. Hasnain, Ed.: 115–119. Elsevier Applied Science. New York.

94. Freedman, B., R. Morash, U. Prager, *et al*. 1984. Effects of harvesting biomass for energy on the nutrient status of long-term productivity of forest stands in Nova Scotia. In *Fifth Canadian Bioenergy R & D Seminar*. S. Hasnain, Ed.: 107–110. Elsevier Applied Science. New York.

95. Chatarpaul, L., D. Burgess & O. Hendrickson. 1984. A comparison of biomass and nutrients removed in whole tree harvesting and conventional (stem only) harvesting. In *Fifth Canadian Bioenergy R & D Seminar*. S. Hasnain, Ed.: 121–125. Elsevier Applied Science. New York.

96. Elobeid, A., S. Tokgoz, D.J. Hayes, *et al*. 2006. *The Long-Run Impact of Corn-Based Ethanol on the Grain, Oilseed, and Livestock Sectors: A Preliminary Assessment*. CARD Briefing Paper 06-BP 49, Center for Agricultural and Rural Development, Iowa State University. Ames, IA, November. www.card.iastate.edu.

97. Westcott, P.C. 2007. *Ethanol Expansion in the United States: How Will the Agriculture Sector Adjust?* FDS-07D-01, Economic Research Service, U.S. Department of Agriculture. Washington, D C. May. www.ers.usda.gov/Publications/FDS/2007/05May/FDS07D01/fds07D01.pdf.

98. Vanwey, L. 2009. Social and distributional impacts of biofuel production. In *Biofuels: Environmental Consequences and Interactions with Changing Land Use*. R. Howarth & S. Bringezu, Eds.: 205–214. Cornell University. Ithaca, NY. Available at: http://cip.cornell.edu/biofuels/.

99. Rajagopal, D., S.E. Sexton, D. Roland-Holst & D. Zilberman. 2007. Challenge of biofuel: filling the tank without emptying the stomach? *Environ. Res. Lett.* **2:** doi:10.1088/1748–9326/2/4/044004. Q17

100. Ewing, M. & S. Msangi. 2009. Biofuels production in developing countries: assessing tradeoffs in welfare and food security. *Environ. Sci. Policy* **12:** 520–528.

101. Phalan, P. 2009. The social and environmental impacts of biofuels in Asia: an overview. *Appl. Energy* **86:** S21–S29.

102. Runge, C.F. & B. Senauer. 2007. How biofuels could starve the poor. *Foreign Affairs* ~~**86:** May/June~~ www.foreignaffairs.org/20070501faessay86305/c-ford-runge-benjamin-senauer/how-biofuels-could-starve-the-poor.html. Q18

103. *The Guardian*. 2007. Massacres and paramilitary land seizures behind the biofuel revolution. June 5. Available at: http://environment.guardian.co.uk/energy/story/0,,2095349,00.html.

104. International Energy Agency. 2008. *Energy Technology Perspectives: Scenarios and Strategies to 2050*. Organization for Economic Cooperation and Development. Paris.

105. Walsh, M.E., D.G. de la Torre Ugarte, H. Shapouri & S.P. Slinsky. 2003. Bioenergy crop production in the United States. *Environ. Resour. Econ.* **24:** 313–333.

106. Lemus, R., E.C. Brummer, K.J. Moore, *et al*. 2002. Biomass yield and quality of 20 switchgrass populations in Southern Iowa, USA. *Biomass Bioenergy* **23:** 433–442.

107. Gleick, P.H. 2009. *The World's Water 2008–2009, The Biennial Report on Freshwater Resources*. Island Press, Washington, DC. www.worldwater.org/data.html.

108. Food and Agriculture Organization of the United Nations. *FAO Water*, web site of the FAO concerned with water, with links to databases and models. www.fao.org/nr/water/.

109. FAO land-use data at Available at: http://faostat.fao.org/faostat/.

110. Davis, S.C., S.W. Diegel & R.G. Bundy. 2008. *Transportation Energy Data Book*, ORNL-6981, Oak Ridge National Laboratory. Oak Ridge, TN. Available at: http://cta.ornl.gov/data/index.shtml.

111. Solley, W.B., R.R. Pierce & H.A. Perlman. 1998. *Estimated Use of Water in the United States in 1995.* U.S. Geological Survey Circular 20, U.S. Government Printing Office. Washington, DC. Available at: http://water.usgs.gov/watuse/pdf1995/html/.

112. de Fraiture, C., M. Giordano & Y. Liao. 2008. Biofuels and implications for agricultural water use: blue impacts of green energy. *Water Policy* **10:** 67–81.
113. Seckler, D., R. Barker & U. Amarasinghe. 1999. Water scarcity in the twenty-first century. *Water Resour. Dev.* **15:** 29–42.
114. Arnell, N.W. 2004. Climate change and global water resources: SRES emissions and socio-economic scenarios. *Glob. Environ. Change* **14:** 31–52.
115. Alcamo, J. & T. Henrichs. 2002. Critical regions: a model-based estimation of world water resources sensitive to global changes. *Aquat. Sci.* **64:** 352–362.
116. Müller, A., J. Schmidhuber, J. Hoogeveen & P. Steduto. 2008. Some insights in the effect of growing bio-energy demand on global food security and natural resources. *Water Policy* **10:** 83–94.
117. Yang, H., Y. Zhou & J. Liu. 2009. Land and water requirements of biofuel and implications for food supply and the environment in China. *Energy Policy* **37:** 1876–1885.
118. Rajagopal, D. 2008. Implications of India's biofuel policies for food, water and the poor. *Water Policy* **10:** 95–106.
119. Alcamo, J., T. Henrichs, P. Döll, *et al*. 2003. Global estimates of water withdrawals and availability under current and future business-as-usual" conditions. *Hydrol. Sci. J.* **48:** 339–348.
120. Serageldin, I. 1995. Water resources management: a new policy for a sustainable future. *Water Resour. Dev.* **11:** 221–232.
121. Varis, O. 2007. Water demands for bioenergy production. *Water Resour. Dev.* **23:** 519–535.
122. National Research Council. 2008. *Water Implications of Biofuels Production in the United States*. Committee on Water Implications of Biofuels Production in the United States, Water and Science Technology Board, Division of Earth and Life Studies, National Research Council, National Academy of Sciences. National Academy Press. Washington, DC. www.nap.edu/catalog/12039.html.
123. Jørgensen, U., T. Dalgaard & E. Steen Kristensen. 2005. Biomass energy in organic farming – the potential role of short rotation coppice. *Biomass Bioenergy* **28:** 237–248.
124. Reijnders, L. 2006. Conditions for sustainability of biomass based fuel use. *Energy Policy* **34:** 863–876.
125. Anex, R.P., L.R. Lynd, M.S. Laser, *et al*. 200. Potential for enhanced nutrient cycling through coupling of agricultural and bioenergy systems. *Crop Sci.* **47:** 1327–1335.
126. Lehmann, J., J. Gaunt & M. Rondon. 2006. Bio-char sequestration in terrestrial ecosystems – a review. *Mitig. Adapt. Strat. Glob. Change* **11:** 395–419.
127. Mathews, J.A. 2008. Carbon-negative biofuels. *Energy Policy* **36:** 940–945.
128. Muller, A. 2009. Sustainable agriculture and the production of biomass for energy use. *Clim. Change* **94:** 319–331.
129. Prabhakar, S.V.R.K. & M. Elder. 2009. Biofuels and resource use efficiency in developing Asia: back to basics. *Appl. Energy* **86:** S30–S36.
130. Johansson, D.J.A. & C. Azar. 2007. A scenario based analysis of land competition between food and bioenergy production in the US. *Clim. Change* **82:** 267–291.
131. Scharlemann, J.P.W. & W.F. Laurance. 2008. How green are biofuels? *Science* **319:** 43–44.
132. Baral, A. & B.R. Bakshi. ~~2008. Hybrid LCA of corn ethanol, gasoline, soybean biodiesel, and diesel, I – accounting for natural capital and net energy analysis. submitted to *Environ. Sci. Technol.*~~ **Q19**
133. Baral, A. & B.R. Bakshi. 2008. *The Role of Ecological Resources and Aggregate Thermodynamic Metrics for Assessing the Life Cycle of Some Biomass and Fossil Fuels.* Department of Chemical and Biomolecular Engineering. Ohio State University. Ohio, OH.
134. Hau, J.L. & B.R. Bakshi. 2004. Expanding exergy analysis to account for ecosystem products and services. *Environ. Sci. Technol.* **38:** 3768–3777.
135. Clift, R. 2003. Metrics for supply chain sustainability. *Clean Technol. Environ. Policy* **5:** 240–247.

Queries

Q1 Author: Please provide a current full postal address (including post/zip code) for the corresponding author.

Q2 Author: Please provide the expanded form of "LCA."

Q3 Author: Please provide the page range for this article in Reference 6.

Q4 Author: Please provide the name and city location of publisher for Reference 7.

Q5 Author: Please provide the name and city location of publisher for Reference 12.

Q6 Author: Papers that have not yet been accepted for publication should not be included in the Reference List; they should be cited in the text as 34, Delucchi "unpublished data." Please update Reference 34 if it has now been published, use "in press" (with journal title details, if appropriate) if it has been accepted for publication, or remove it from Reference List and change to "34, Delucchi unpublished data" in the text if it has not yet been accepted.

Q7 Author: Please provide the correct page range for this article in Reference 37.

Q8 Author: If this Reference 39 is not a one-page article please supply the first and last pages for this article.

Q9 Author: Please provide the page range for this article in Reference 46.

Q10 Author: Papers that have not yet been accepted for publication should not be included in the Reference List; they should be cited in the text as 47, Jacobson "unpublished data." Please update Reference 47 if it has now been published, use "in press" (with journal title details, if appropriate) if it has been accepted for publication, or remove it from Reference List and change to "47, Jacobson unpublished data" in the text if it has not yet been accepted.

Q11 Author: Please provide the page range for this article in Reference 48.

Q12 Author: Please provide the page range for this article in Reference 57.

Q13 Author: Please provide the name and city location of publisher for Reference 61.

Q14 Author: If this Reference 80 is not a one-page article please supply the first and last pages for this article.

Q15 Author: Please supply the initials for Küsters in Reference 85.

Q16 Author: If this Reference 91 is not a one-page article please supply the first and last pages for this article.

Q17 Author: Please provide the page range for this article in Reference 99.

Q18 Author: Please provide the page range for this article in Reference 102.

Q19 Author: Papers that have not yet been accepted for publication should not be included in the Reference List; they should be cited in the text as 132, Baral "unpublished data." Please update Reference 132 if it has now been published, use "in press" (with journal title details, if appropriate) if it has been accepted for publication, or remove it from Reference List and change to "132, Baral unpublished data" in the text if it has not yet been accepted.