Reconsidering bioenergy given the urgency of climate protection

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The use of bioenergy has grown rapidly in recent years, driven by policies partly premised on the belief that bioenergy can contribute to carbon dioxide (CO_2) emissions mitigation. However, the experience with bioenergy production and the pressure it places on land, water, biodiversity, and other natural resources has raised questions about its merits. Recent studies offer a lesson: Bioenergy must be evaluated by addressing both the stocks and flows of the carbon cycle. Doing so clarifies that increasing the rate of carbon uptake in the biosphere is a necessary condition for atmospheric benefit, even before considering production-related lifecycle emissions and leakage effects due to land-use change. To maximize the role of the biosphere in mitigation, we must focus on and start with measurably raising rates of net carbon uptake on land—rather than seeking to use biomass for energy. The most ecologically sound, economical, and scalable ways to accomplish that task are by protecting and enhancing natural climate sinks.

Hence, a major reprioritization of climate-related research, policy, and investment is urgently required, a move away from bioenergy and toward terrestrial carbon management (TCM). Researchers and

Rather than prioritizing bioenergy production, researchers and policymakers should pursue carbon management initiatives such as the reforestation project pictured here. Such efforts are much more likely to significantly reduce atmospheric CO_2 concentrations in the near and medium term. Image courtesy of Lisa M. Dellwo (photographer).

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policymakers must pursue actionable mitigation approaches that have the best chance of significantly reducing atmospheric CO_2 concentrations in the near and medium term. When the biosphere is engaged, the emphasis should shift toward large-scale natural climate solutions, including the protection, restoration, and enhancement of forests and other terrestrial carbon sinks.

As energy researchers and policy analysts have confronted the global warming problem over the past several decades, industrial-scale bioenergy found strong support as a mitigation option (1). The vision has been to replace the linear flow of fossil carbon from the Earth's crust to the atmosphere with a circular flow of biogenic carbon. Wood from sustainably managed forests could displace coal for power generation. Liquid biofuels from various feedstocks could displace petroleum for transportation. If such substitutions could be accomplished efficiently (after accounting for production-related greenhouse gas emissions), the result would be a net reduction of CO_2 emissions from the use of carbon-based fuels. The assumption that bioenergy is inherently carbon neutral, i.e., that its production and use involve a balanced exchange of biogenic carbon with the atmosphere, is the basis of this vision and is built into the lifecycle assessment (LCA) methods used for energy policy (2, 3). It is also used in international carbon accounting, which omits biogenic CO_2 emitted from the energy sector because the atmospheric impact is assumed to be handled in the land-use sector (4).

Such a bioenergy vision has fostered major research and development (R&D) investments in advanced biofuels, utilizing cellulosic biomass and other unconventional feedstocks. Large-scale bioenergy use is often featured in climate-stabilization scenarios (5, 6). Many integrated assessment modeling (IAM) scenarios for avoiding severe climate change assume extensive use of energy crops as well as bioenergy with carbon capture and storage (BECCS) (7, 8). However, IAM is only illustrative and involves many broad assumptions about future technology, land-use patterns, and economic behavior (9, 10).

Although researchers acknowledge the risks to biodiversity and ecosystem services, much of the literature explicitly or implicitly advocates the pursuit of beneficial bioenergy options (11, 12). LCA studies often conclude that current biofuels, such as ethanol and biodiesel from grains, sugarcane, and oilseeds, offer at least modest CO_2 reductions compared with the fossil fuels they replace (13, 14). They also project much greater benefits for advanced biofuels (11, 12, 14). Justified in part by such findings, renewable-energy mandates, subsidies, and other supportive policies have been driving an expansion of bioenergy, including the combustion of both forest products and liquid biofuels derived from a variety of crops.

The degree of disagreement about the net benefits of bioenergy has grown as modeling tools became more complex, especially when models attempt to assess land-use implications (9, 10, 15). Bioenergy use at scales needed to significantly replace fossil fuels requires large areas of land (16). Further demands for productive land, whether forest or cropland, amplify the many factors that drive land-use change globally (17). Bioenergy displaces land from prior uses, resulting in both direct (18) and indirect (19) land-use change. This leads to the difficult conundrum of carbon debt, i.e., the time it takes for the release of carbon stocks linked to bioenergy expansion to be paid back through future carbon uptake, which can be decades (20, 21). Moreover, the realities of bioenergy production exacerbate the effects of industrial-scale agriculture on soil health, water quality, biodiversity, and other ecosystem services (22–24). The result is a dissonance between positive views of bioenergy based on prospective modeling and negative views based on assessing its real-world impacts in light of the limitations of land-use governance and available technology.

Given the urgency of the climate problem and the opportunity costs (both ecologic and economic) of claiming large areas of land for bioenergy, much greater clarity is needed. The pressing question is not about the ideal mix of technology for a future world. Rather, it is about what is actionable today for reducing atmospheric CO_2 buildup with maximal confidence, minimal risk, and a realistic appraisal of technology and resource constraints. When the biosphere is involved, the issue must be analyzed in terms of carbon stocks and flows (25). The carbon cycle is a dynamic process in which the atmosphere exchanges carbon with pools of various lifetimes in the biosphere, mixed with flows of fossil carbon from the lithosphere (26). This cycle has not been in equilibrium since humans began appropriating net primary production at large scales many generations ago. Engaging the biosphere in an attempt to reduce atmospheric CO_2 buildup is itself a dynamic perturbation of the existing stocks and flows.

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The assumption that bioenergy is inherently carbon-neutral, which is based on static forms of carbon accounting, is a major error (27). Viewed objectively, it is quite a sweeping assumption: It asserts that a carbon flow into the atmosphere at one place and time (from bioenergy combustion) is automatically and fully offset by carbon uptake at another place and time (on ecologically productive land). Scientifically speaking, there is neither a sound basis nor a need to make this assumption. The extent to which the CO_2 emitted from bioenergy use is balanced by CO_2 uptake is an empirical question.

A first-order stock-and-flow analysis of the key carbon flows clarifies the situation (28). Combustion chemistry dictates that replacing a fossil fuel with bioenergy does not reduce the rate at which carbon flows into the atmosphere. Beyond reducing the combustion of chemically carbon-based fuels or capturing and sequestering CO_2 from their combustion, mitigation requires increasing the rate at which CO_2 is removed from the atmosphere. Therefore, for bioenergy to be potentially beneficial, it is not enough for its carbon merely to be biogenic; it is necessary that it be obtained in a way that increases the rate of net carbon uptake by the biosphere. Net uptake is given by net ecosystem production (NEP), and so the requisite condition is represented as $d(NEP)/dt > 0$. For an increase in NEP to be directly credited to bioenergy, it must be evaluated locally on the land from which the biomass feedstock is obtained.

The above relation is only the necessary condition for mitigation. Sufficiency requires evaluating production-related emissions, both direct and indirect, e.g., as addressed by LCA. Because it provides a necessary condition, changes in NEP constrain the offset of CO_2 emissions achieved with bioenergy. That evaluation is rarely performed despite the data and methods available for doing so. A recent analysis found that the NEP gain on cropland was enough to offset only 37% of the increase in fuel-related biogenic CO_2 emissions over the 2008–2013 period of US biofuel expansion (29). That result provides a large-scale, real-world counterexample to the 100% offset (inherent carbon neutrality) widely assumed in LCA modeling and policy-related carbon accounting.

Therefore, the focus of research and policy should not be substituting biofuels for fossil fuels downstream in the energy sector but rather on increasing the rate at which CO_2 is removed from the atmosphere upstream in the land-use sector. This requires TCM, including the many opportunities for "natural climate solutions" that protect and rebuild carbon stocks in the biosphere. Recent work has highlighted the very large and relatively low-cost potential of TCM (30). Largely by avoiding deforestation and by reforesting harvested areas, up to one-third of current CO_2 emissions from fossil fuels could be sequestered in the biosphere. Because wetlands are areas of impeded decomposition, they also contribute significant positive NEP, implying further benefits through wetland preservation and restoration, discounted by their higher emissions of methane. TCM could be expanded over large areas given substantially increased financial support for implementation. Increased research support can enhance the effectiveness of TCM and enable continuous improvements in the face of growing pressures on ecosystems from human activities and the changing climate itself.

Carbon uptake is the high point of biologically based mitigation potential; subsequent harvesting and processing of biomass release at least some of the newly fixed carbon as CO_2 back into the atmosphere. All currently commercial forms of bioenergy require land and risk carbon debts that last decades into the future. Given the urgency of the climate problem, it is puzzling why some parties find these excess near-term CO_2 emissions acceptable. In contrast, TCM can keep carbon out of the atmosphere for many decades. Even though such options can have permanence challenges, they offer substantial near- and medium-term CO_2 mitigation, providing time for R&D to improve the durability of terrestrial sinks and otherwise keep carbon sequestered.

An immediate focus on TCM does not eliminate an eventual role for bioenergy or BECCS. The literature is replete with modeling of hypothetical bioenergy systems that presume the availability of advanced biomass conversion technologies and idealized, "sustainable" land use. However, such technologies have failed viability after decades of research. One cannot rule out breakthroughs in algal technologies or other options that might be scaled up without adverse ecological impacts. Nevertheless, any option that exploits biogenic carbon in the quantities needed to meaningfully replace fossil carbon in the energy supply will require widespread, careful scientific management of carbon stocks and flows throughout the biosphere. Primary production cannot be taken for granted, as is the case now in bioenergy modeling that invokes an assumption of biogenic carbon neutrality to rationalize strategies that remove biomass at vast scales for combustion.

In short, a sound understanding of carbon-cycle dynamics shows that now and for the reasonably foreseeable future, the promotion of bioenergy is ill-premised for climate protection. This is particularly true if one respects the limited amount of ecologically productive land available for supplying food and fiber as well as sustaining and restoring biodiverse habitats. In fact, TCM and careful assessment of NEP are preconditions for land-based bioenergy to become verifiably beneficial. A major reprioritization of energy policy and research is therefore in order, away from bioenergy and a toward a high level of support for TCM. Indeed, neither biofuels nor BECCS may be needed in the long run. A future world that respects the climate, ecosystem, and other natural resource constraints may well be built on truly carbon-free energy carriers, nonbiological mechanisms for carbon sequestration, and extensive recarbonization of the biosphere.

1 Bauen A, et al. (2009) Bioenergy: A sustainable and reliable energy source. A review of status and prospects. Available at www.ieabioenergy.com/publications/main-report-bioenergy-a-sustainable-and-reliable-energy-source-a-review-of-status-and-prospects/. Accessed August 16, 2018.

2 European Union (2009) Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources. *Off J Eur Union* 5.6.2009:16–62.

3 US Environmental Protection Agency (2010) Renewable fuel standard program (RFS2) regulatory impact analysis (Environmental Protection Agency, Washington, DC), Technical Report EPA-420-R-10-006.

4 Intergovernmental Panel on Climate Change (2006) IPCC guidelines for national greenhouse gas inventories. Available at www.ipcc-nggip.iges.or.jp/public/2006gl/index.html. Accessed August 16, 2018.

5 Gillingham KT, Smith SJ, Sands RD (2008) Impact of bioenergy crops in a carbon dioxide constrained world: An application of the MiniCAM energy-agriculture and land use model. *Mitig Adapt Strateg Glob Chang* 13:675–701.
6 Popp A, et al. (2011) The economic potential of bioenergy for climate change mitigation with special attention given to implications for the land system. *Environ Res Lett* 6:034017.
7 Edmonds J, et al. (2013) Can radiative forcing be limited to 2.6 Wm^{-2} without negative emissions from bioenergy and CO_2 capture and storage? *Clim Change* 118:29–43.
8 Smith P, et al. (2015) Biophysical and economic limits to negative CO_2 emissions. *Nat Clim Chang* 6:42.
9 Intergovernmental Panel on Climate Change (2012) Special report on renewable energy sources and climate change mitigation. Available at https://www.ipcc.ch/pdf/special-reports/srren/SRREN_FD_SPM_final.pdf. Accessed August 16, 2018.
10 Creutzig F, et al. (2012) Can bioenergy assessments deliver? *Econ Energy Environ Policy* 1:65–82.
11 Tilman D, et al. (2009) Energy. Beneficial biofuels–The food, energy, and environment trilemma. *Science* 325:270–271.
12 Robertson GP, et al. (2017) Cellulosic biofuel contributions to a sustainable energy future: Choices and outcomes. *Science* 356:eaal2324.
13 Farrell AE, et al. (2006) Ethanol can contribute to energy and environmental goals. *Science* 311:506–508.
14 Wang MQ, et al. (2011) Energy and greenhouse gas emission effects of corn and cellulosic ethanol with technology improvements and land use changes. *Biomass Bioenergy* 35:1885–1896.
15 Schulze E-D, Körner C, Law BE, Haberl H, Luyssaert S (2012) Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral. *Glob Change Biol Bioenergy* 4:611–616.
16 van Vuuren DP, van Vliet J, Stehfest E (2009) Future bio-energy potential under various natural constraints. *Energy Policy* 37:4220–4230.
17 Lambin EF, Meyfroidt P (2011) Global land use change, economic globalization, and the looming land scarcity. *Proc Natl Acad Sci USA* 108:3465–3472.
18 Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P (2008) Land clearing and the biofuel carbon debt. *Science* 319:1235–1238.
19 Searchinger T, et al. (2008) Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science* 319:1238–1240.
20 Melillo JM, et al. (2009) Indirect emissions from biofuels: How important? *Science* 326:1397–1399.
21 Zanchi G, Pena N, Bird N (2010) The upfront carbon debt of bioenergy. *Joanneaum Res Graz* 56:1–54.
22 Kluts I, Wicke B, Leemans R, Faaij A (2017) Sustainability constraints in determining European bioenergy potential: A review of existing studies and steps forward. *Renew Sustain Energy Rev* 69:719–734.
23 Hoekman SK, Broch A, Liu X (2018) Environmental implications of higher ethanol production and use in the U.S.: A literature review. Part I–Impacts on water, soil, and air quality. *Renew Sustain Energy Rev* 81:3140–3158.
24 Hoekman SK, Broch A (2018) Environmental implications of higher ethanol production and use in the U.S.: A literature review. Part II–Biodiversity, land use change, GHG emissions, and sustainability. *Renew Sustain Energy Rev* 81:3159–3177.
25 Schlamadinger B, et al. (1997) Towards a standard methodology for greenhouse gas balances of bioenergy systems in comparison with fossil energy systems. *Biomass Bioenergy* 13:359–375.
26 Schlesinger WH, Bernhardt ES (2013) *Biogeochemistry: An Analysis of Global Change* (Academic Press, New York), 3rd Ed.
27 Haberl H, et al. (2012) Correcting a fundamental error in greenhouse gas accounting related to bioenergy. *Energy Policy* 45:18–23.
28 DeCicco JM (2013) Biofuel's carbon balance: Doubts, certainties and implications. *Clim Change* 121:801–814.
29 DeCicco JM, et al. (2016) Carbon balance effects of U.S. biofuel production and use. *Clim Change* 138:667–680.
30 Griscom BW, et al. (2017) Natural climate solutions. *Proc Natl Acad Sci USA* 114:11645–11650.