complement prior studies that highlight the importance of short- and medium-lived pollutants (*14–17*).

The top 10 pollutant-generating activities contributing to net RF (positive RF minus negative RF) in year 20 are shown in the bottom chart, page 526), which takes into account the emission of multiple pollutants from each source activity (*18*). The seven sources that appear only on the left side (purple bars) would be overlooked by mitigation strategies focusing exclusively on long-lived pollutants.

The distinctly different sources of near-term and long-term RF lend themselves to the aforementioned two-pronged mitigation approach. This decoupling is convenient for policy design and implementation; whereas the importance of long-term climate stabilization is clear, the perceived urgency of near-term mitigation will evolve with our knowledge of the climate system. Additionally, optimal near-term mitigation strategies will reflect decadal oscillations (*19*), seasonal and regional variations (*20*, *21*), and evolving knowledge of aerosol-climate effects (*22*, *23*) and methane-atmosphere interactions (*22*)—considerations unique to the near term.

Thus, short- and medium-lived sources (black carbon, tropospheric ozone, and methane) must be regulated separately and dynamically. The long-term mitigation treaty should focus exclusively on steady reduction of long-lived pollutants. A separate treaty for short- and medium-lived sources should include standards that evolve based on periodic recommendations of an independent international scientific panel. The framework of "best available control technology" (strict) and "lowest achievable emissions rate" (stricter) from the U.S. Clean Air Act (*24*) can be used as a model.

Such a two-pronged institutional framework would reflect the evolving scientific understanding of near-term climate change, the scientific certainty around long-term climate change, and the opportunity to separately adjust the pace of near-term and long-term mitigation efforts.

References and Notes

1. D. Archer *et al.*, *Annu. Rev. Earth Planet. Sci.* **37**, 117 (2009).
2. The e-folding time (required to decrease to 37% of original airborne amount) is on the order of days to weeks for short-lived pollutants (e.g., black and organic carbon, tropospheric ozone, and sulfur dioxide), a decade for medium-lived (e.g., methane and some halocarbons), and a century for long-lived (e.g., nitrous oxide, some halocarbons). CO_2 takes roughly a century to reach 37%, then decays more slowly over millennia.
3. C. P. McMullen, J. Jabbour, Eds., *Climate Change Science Compendium 2009* (U.N. Environment Programme, Nairobi, EarthPrint, 2009); www.unep.org/compendium2009/.
4. S. Solomon *et al.*, *Climate Change 2007: The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report of the IPCC* (Cambridge Univ. Press, New York, 2007).
5. S. Rahmstorf *et al.*, *Science* **316**, 709 (2007).
6. J. B. Smith *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **106**, 4133 (2009).
7. A. Sokolov *et al.*, *J. Clim.* **22**, 5175 (2009).
8. T. Stocker, *Quat. Sci. Rev.* **19**, 301 (2000).
9. T. M. Lenton *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **105**, 1786 (2008).
10. J. Hansen *et al.*, *Open Atmos. Sci. J.* **2**, 217 (2008).
11. RF is a property of the climate at a point in time. Increases in RF create planetary energy imbalance, with more incoming solar radiation than outgoing infrared radiation and a warming effect on the system.
12. T. F. Stocker, A. Schmittner, *Nature* **388**, 862 (1997).
13. R. B. Alley *et al.*, *Science* **299**, 2005 (2003).
14. J. Hansen *et al.*, *Philos. Trans. R. Soc. London Ser. A* **365**, 1925 (2007).
15. P. K. Quinn *et al.*, *Atmos. Chem. Phys.* **8**, 1723 (2008).
16. M. Z. Jacobson, *J. Geophys. Res. Atmos.* **107**, 4410 (2002).
17. F. C. Moore, M. C. MacCracken, *Intl. J. Strategic Change Mgmt.* **1**, 42 (2009).
18. D. Koch, T. C. Bond, D. Streets, N. Unger, *Geophys. Res. Lett.* **34**, L05821 (2007).
19. K. Trenberth *et al.*, in (*4*), pp. 235–336.
20. D. Koch, T. Bond, D. Streets, N. Unger, G. van der Werf, *J. Geophys. Res.* **112**, D02205 (2007).
21. A. Stohl, *J. Geophys. Res.* **111**, D11306 (2006).
22. P. Forster *et al.*, in (*4*), pp. 129–234.
23. V. Ramanathan, G. Carmichael, *Nat. Geosci.* **1**, 221 (2008).
24. U.S. Clean Air Act, www.epa.gov/oar/caa/.
25. The same analysis applied to the IPCC's SRES marker scenarios (A1, A2, B1, and B2) (*26*) produces results that fall largely within the bounds of these two scenarios (fig. S1).
26. N. Nakićenović, R. Swart, Eds., *Special Report on Emissions Scenarios* (IPCC, Cambridge Univ. Press, Cambridge, 2000).
27. Data for year 2000 RF are based on (*14*), emissions are from (*28*), decay rates are based on the lifetimes on p. 212 in (*22*) and historical CO_2 decay is calculated according to p. 824 in (*29*). Growth rates are from (*28*) and (*30*). Zero growth of emissions assumed for BC, OC, SO_2, and halocarbons Each year's RF for short-lived pollutants (BC, OC, O_3, SO_2) is due only to emissions in that year; thus, the RF does not accumulate from one year to the next. The contributions of black carbon and ozone are conservative, as they do not reflect recent near-double estimates of black carbon's RF (*23*) nor recent estimates of ozone's indirect land sink effect (*31*).
28. EDGAR 3.2 (www.mnp.nl/edgar/model/).
29. G. Meehl *et al.*, in (*4*), pp. 747–845.
30. Climate Analysis Indicators Tool v6.0 (http://cait.wri.org).
31. S. Sitch, P. M. Cox, W. J. Collins, C. Huntingford, *Nature* **448**, 791 (2007).
32. T. C. Bond *et al.*, *Global Biogeochem. Cycles* **21**, GB2018 (2007).

33. The author thanks J. Harte for providing encouragement and critique.

Supporting Online Material
www.sciencemag.org/cgi/content/full/326/5952/526/DC1

10.1126/science.1177042

CLIMATE CHANGE

Fixing a Critical Climate Accounting Error

Timothy D. Searchinger,[1]* Steven P. Hamburg,[2]* Jerry Melillo,[3] William Chameides,[4] Petr Havlik,[5] Daniel M. Kammen,[6] Gene E. Likens,[7] Ruben N. Lubowski,[2] Michael Obersteiner,[5] Michael Oppenheimer,[1] G. Philip Robertson,[8] William H. Schlesinger,[7] G. David Tilman[9]

Rules for applying the Kyoto Protocol and national cap-and-trade laws contain a major, but fixable, carbon accounting flaw in assessing bioenergy.

The accounting now used for assessing compliance with carbon limits in the Kyoto Protocol and in climate legislation contains a far-reaching but fixable flaw that will severely undermine greenhouse gas reduction goals (*1*). It does not count CO_2 emitted from tailpipes and smokestacks when bioenergy is being used, but it also does not count changes in emissions from land use when biomass for energy is harvested or grown. This accounting erroneously treats all bioenergy as carbon neutral regardless of the source of the biomass, which may cause large differences in net emissions. For example, the clearing of long-established forests to burn wood or to grow energy crops is counted as a 100% reduction in energy emissions despite causing large releases of carbon.

Several recent studies estimate that this error, applied globally, would create strong incentives to clear land as carbon caps tighten. One study (*2*) estimated that a global CO_2 target of 450 ppm under this accounting would cause bioenergy crops to expand to displace virtually all the world's natural forests and savannahs by 2065, releasing up to 37 gigatons (Gt) of CO_2 per year (compa-

[1]Princeton University, Princeton, NJ 08544, USA. [2]Environmental Defense Fund, Boston, MA 02108, and Washington, DC 20009, USA. [3]Marine Biological Laboratory, Woods Hole, MA 02543, USA. [4]Duke University, Durham, NC 27708, USA. [5]International Institute for Applied Systems Analysis, Laxenburg 2361, Austria. [6]University of California at Berkeley, Berkeley, CA 94720, USA. [7]Cary Institute of Ecosystem Studies, Millbrook, NY 12545, USA. [8]Michigan State University, Hickory Corners, MI 49060, USA. [9]University of Minnesota, St. Paul, MN 55108, USA.

*Authors for correspondence. E-mail: shamburg@edf.org (S.P.H.); tsearchi@princeton.edu (T.D.S.).

rable to total human CO_2 emissions today). Another study predicts that, based solely on economic considerations, bioenergy could displace 59% of the world's natural forest cover and release an additional 9 Gt of CO_2 per year to achieve a 50% "cut" in greenhouse gases by 2050 (*3*). The reason: When bioenergy from any biomass is counted as carbon neutral, economics favor large-scale land conversion for bioenergy regardless of the actual net emissions (*4*).

The potential of bioenergy to reduce greenhouse gas emissions inherently depends on the source of the biomass and its net land-use effects. Replacing fossil fuels with bioenergy does not by itself reduce carbon emissions, because the CO_2 released by tailpipes and smokestacks is roughly the same per unit of energy regardless of the source (*1*, *5*). Emissions from producing and/or refining biofuels also typically exceed those for petroleum (*1*, *6*). Bioenergy therefore reduces greenhouse emissions only if the growth and harvesting of the biomass for energy captures carbon above and beyond what would be sequestered anyway and thereby offsets emissions from energy use. This additional carbon may result from land management changes that increase plant uptake or from the use of biomass that would otherwise decompose rapidly. Assessing such carbon gains requires the same accounting principles used to assign credits for other land-based carbon offsets.

For example, if unproductive land supports fast-growing grasses for bioenergy, or if forestry improvements increase tree growth rates, the additional carbon absorbed offsets emissions when burned for energy. Energy use of manure or crop and timber residues may also capture "additional" carbon. However, harvesting existing forests for electricity adds net carbon to the air. That remains true even if limited harvest rates leave the carbon stocks of regrowing forests unchanged, because those stocks would otherwise increase and contribute to the terrestrial carbon sink (*1*). If bioenergy crops displace forest or grassland, the carbon released from soils and vegetation, plus lost future sequestration, generates carbon debt, which counts against the carbon the crops absorb (*7*, *8*).

The Intergovernmental Panel on Climate Change (IPCC) has long realized that bioenergy's greenhouse effects vary by source of biomass and land-use effects. It also recognizes that when forests or other plants are harvested for bioenergy, the resulting carbon release must be counted either as land-use emissions or energy emissions but not both. To avoid double-counting, the IPCC assigns the CO_2 to the land-use accounts and exempts bioenergy emissions from energy accounts (*5*). Yet it warns, because "fossil fuel substitution is already 'rewarded'" by this exemption, "to avoid underreporting . . . any changes in biomass stocks on lands . . . resulting from the production of biofuels would need to be included in the accounts" (*9*).

This symmetrical approach works for the reporting under the United Nations Framework Convention on Climate Change (UNFCCC) because virtually all countries report emissions from both land and energy use. For example, if forests are cleared in Southeast Asia to produce palm biodiesel burned in Europe, Europe can exclude the tailpipe emissions as Asia reports the large net carbon release as land-use emissions.

However, exempting emissions from bioenergy use is improper for greenhouse gas regulations if land-use emissions are not included. The Kyoto Protocol caps the energy emissions of developed countries. But the protocol applies no limits to land use or any other emissions from developing countries, and special crediting rules for "forest management" allow developed countries to cancel out their own land-use emissions as well (*1*, *10*). Thus, maintaining the exemption for CO_2 emitted by bioenergy use under the protocol (*11*) wrongly treats bioenergy from all biomass sources as carbon neutral, even if the source involves clearing forests for electricity in Europe or converting them to biodiesel crops in Asia .

This accounting error has carried over into the European Union's cap-and-trade law and the climate bill passed by the U.S. House of Representatives (*1*, *12*, *13*). Both regulate emissions from energy but not land use and then erroneously exempt CO_2 emitted from bioenergy use. In theory, the accounting system would work if caps covered all land-use emissions and sinks. However, this approach is both technically and politically challenging as it is extremely hard to measure all land-use emissions or to distinguish human and natural causes of many emissions (e.g., fires).

The straightforward solution is to fix the accounting of bioenergy. That means tracing the actual flows of carbon and counting emissions from tailpipes and smokestacks whether from fossil energy or bioenergy. Instead of an assumption that all biomass offsets energy emissions, biomass should receive credit to the extent that its use results in additional carbon from enhanced plant growth or from the use of residues or biowastes. Under any crediting system, credits must reflect net changes in carbon stocks, emissions of non-CO_2 greenhouse gases, and leakage emissions resulting from changes in land-use activities to replace crops or timber diverted to bioenergy (*1*).

Separately, Europe and the United States have established legal requirements for minimum use of biofuels, which assess greenhouse gas consequences based on life-cycle analyses that reflect some land-use effects (*1*, *14*). Such assessments vary widely in comprehensiveness, but none considers biofuels free from land-based emissions. Yet the carbon cap accounting ignores land-use emissions altogether, creating its own large, perverse incentives.

Bioenergy can provide much energy and help meet greenhouse caps, but correct accounting must provide the right incentives.

References and Notes

1. Additional references supporting the themes of this Policy Forum can be found in the supporting online material.
2. M. Wise *et al.*, *Science* **324**, 1183 (2009).
3. J. M. Melillo *et al.*, *Unintended Environmental Consequences of a Global Biofuel Program* (MIT Joint Program Report Series, Massachusetts Institute of Technology, Cambridge, MA, 2009).
4. International Energy Agency, *Energy Technology Perspectives: In Support of the G8 Plan of Action: Scenarios and Strategies to 2050* [Organization for Economic Cooperation and Development (OECD)/IEA, Paris, 2008].
5. IPCC, *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, prepared by the National Greenhouse Gas Inventories Programme [Institute for Global Environmental Strategies (IGES), Tokyo, Japan, 2007].
6. E. Manichetti, M. Otto, in *Biofuels: Environmental Consequences and Interactions with Changing Land Use: Proceedings of the Scientific Committee on Problems of the Environment*, R. W. Howarth, and S. Bringezu, Eds. (Cornell Univ. Press, Ithaca, NY, 2009), pp. 81–109.
7. T. Searchinger *et al.*, *Science* **319**, 1238 (2008).
8. J. Fargione, J. Hill, D. Tilman, S. Polasky, P. Hawthorne, *Science* **319**, 1235 (2008).
9. R. Watson *et al.*, Eds., *Land Use, Land-Use Change, and Forestry* (IPCC, Cambridge Univ. Press, Cambridge, 2000).
10. UNFCCC, *Report of the Conference of the Parties on Its Seventh Session: Action taken by the COP* (FCCC/CP/20001/13/Add.1, UNFCCC, Geneva, 2002), Addendum, part 2.
11. UNFCCC, *Updated UNFCCC reporting guidelines on annual inventories following incorporation of the provisions of decision 14/CP.11* [FCCC/Subsidiary Body for Scientific and Technological Advice (SBSTA)/2006/9, Geneva, 2006], p. 23.
12. European Commission, *Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003*, Official Journal of the European Union L 275, 25.10.2003.
13. The American Clean Energy and Security Act of 2009, H.R. 2454, 111th Cong., 1st Sess. (as passed by U.S. House of Representatives July 2009).
14. T. D. Searchinger, in *Biofuels: Environmental Consequences and Interactions with Changing Land Use: Proceedings of the Scientific Committee on Problems of the Environment,* R. W. Howarth and S. Bringezu, Eds. (Cornell Univ. Press, Ithaca, NY, 2009), pp. 37–52.

15. The authors express thanks for the support of the German Marshall Fund of the United States.

Supporting Online Material

www.sciencemag.org/cgi/content/full/326/5952/527/DC1

10.1126/science.1178797