the Advanced Technology Program.) Second, the regional disparity highlighted in my Policy Forum did not relate to the concentration of awardees. Rather, I emphasized the very poor performance of awardees in regions without a vibrant high-technology community already.

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Carbon Cost of Applying Nitrogen Fertilizer

When the addition of nitrogen (N) fertilizer leads to increased crop biomass, it also augments carbon (C) inputs to the soil and, hence, often increases soil organic matter. Consequently, the efficient use of fertilizer N to increase crop production has also been found valuable for sequestering atmospheric carbon in soil. William H. Schlesinger, however, in his Policy Forum "Carbon sequestration in soils" (*Science*'s Compass, 25 June 1999, p. 2095) analyzes results from a 20-year experiment in Kentucky on conventional-till and no-till corn (*1*) and concludes that "the full carbon cost of N fertilizer…would effectively negate any net carbon sink as a result of the application of the fertilizer." These costs include the CO_2-C emitted during fertilizer manufacture, storage, transport, and application. The three carbon cost factors (moles of CO_2-C emitted per mole of N applied) documented by Schlesinger are 0.375 (stoichiometry of Haber-Bosch reaction), 0.58 (carbon cost of fertilizer manufacture) (*2*), and 1.436 (carbon cost of fertilizer manufacture, storage, transport, and application) (*3, 4*).

We analyzed the same data and found that they do not support the conclusion that the carbon costs of N fertilizer negate the associated carbon sequestered in soil. Using the cost factor of 0.58 leads to ranges of CO_2-C released from fertilizer (as a proportion of sequestration) of 11 to 27% under conventional-till practices and 9 to 19% under no-till practices. The highest factor (1.436) and the fertilizer rate with the highest carbon cost would make the proportional costs increase by a factor of 2.48 to 66% under conventional tillage and 48% under no tillage—not the 100% required to negate any net carbon sequestration. Schlesinger bases his conclusion on the use of an unrealistically high N application rate of 336 kilograms per hectare per year (kg ha^{-1} year^{-1}). Thus, even with the most comprehensive (conservative) cost factor and highest N rate, the carbon cost of fertilizer N to increase crop production is less than the carbon sequestered in soil at the Kentucky site.

Farmers, however, add nutrients to soils to replenish those exported with harvested products in a way that makes economic sense. For example, nonfertilized corn in the Kentucky experiment removed on average 65 kg N ha^{-1} year^{-1}, whereas corn fertilized with 84 kg N ha^{-1} year^{-1} removed 97 kg N ha^{-1} year^{-1}. How much more nitrogen will farmers add? The answer depends on crop response to fertilizer, fertilizer price, and grain price. Using data from the Kentucky experiment and setting marginal cost equal to marginal return, with corn prices at $78 per megagram and fertilizer at $0.50 per kilogram, we calculate that the optimum rate of N application would be 133 kg N ha^{-1} year^{-1}, regardless of tillage method (*5*). Proper fertilization, in combination with reduced tillage, can produce net carbon sequestration in soil and sustain productivity.

Young organic matter extracted after 13 years from soil receiving no N (above) compared with soil receiving N at 50 kg ha^{-1} year^{-1} (right). Black material is charcoal.

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We conclude that N fertilizers, when used to increase crop biomass under the conditions of the Kentucky data, result in positive net carbon sequestration. Carbon sequestration in soils has limits, and it is sensitive to management, soil conditions, and climate. However, the practice offers one way for society to reduce the potential for undesirable climatic change. Failure to recognize its value may lead not only to loss of future opportunities for soil carbon sequestration, but also to policies that inadvertently eliminate carbon sequestration that accrues from progressive agricultural practices.

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1. I. Ismail *et al.*, *Soil Sci. Soc. Am. J.* **58**, 193 (1994). The Kentucky experiment accommodated four N rates (0 to 336 kg ha^{-1} year^{-1}) and registered significant changes in soil C content (www.sciencemag.org/feature/data/1042216.shl).

2. Intergovernmental Panel on Climate Change, *Revised 1996 Guidelines for National Greenhouse Gas Inventories, Reference Manual* (Organization for Economic Cooperation and Development, Washington, DC, 1996).
3. M. G. Bhat, B. B. English, A. F. Thurlow, H. O. Nyangito, *Tech. Rep. ORNL/Sub/90-99732/2* (Oak Ridge National Laboratory, Oak Ridge, TN 1994).
4. R. C. Izaurralde *et al.*, in *Management of Carbon Sequestration in Soil*, R. Lal *et al.*, Eds. (CRC Press, Boca Raton, FL, 1998), pp. 433–446.
5. The United States Department of Agriculture–Economic Research Service national average of N application on corn for the period 1982–1991 is 150 kg N ha^{-1} $year^{-1}$.
6. Work prepared under contract number DE-AC06-76RLO 1830, U.S. Department of Energy/Office of Science.

Response

In the face of increasing environmental problems associated with excessive additions of reactive nitrogen to the environment (*1*), one must be careful to evaluate all policies that would further the use of inorganic N fertilizers in agriculture. It is noteworthy, for example, that the mean use of N fertilizer on corn in the United States [150 kg ha^{-1} $year^{-1}$ (*2*)] is already greater than the economic optimum level calculated by Izaurralde *et al.* for cornfields in Kentucky. Although the carbon costs of N fertilizer discount only 66% of the mean carbon sequestration in the cornfields of Kentucky, other studies, edited for space from my original Policy Forum, have discounts greater than 100% (*3*). In all cases, the marginal CO_2 cost of increasing N fertilizer use exceeds the marginal gain of carbon sequestration in soils, especially those under no-till management. Thus, recommendations for a greater use of N fertilizer (*4*), above 1990 baseline activity, are unlikely to contribute significantly to Kyoto credits through enhanced carbon sequestration in agricultural soils and are very likely to contribute to excessive losses of N to surface- and groundwaters (*1*).

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References and Notes

1. P. Vitousek *et al.*, *Ecol. Applica.* 7, 737 (1997).
2. The United States Department of Agriculture–Economic Research Service national average of N application on corn for the period 1982–1991.
3. W. H. Schlesinger, *Agric. Ecosystem. Environ.*, in press.
4. R. Lal *et al.*, *J. Soil Water Conserv.* **54**, 374 (1999).

CORRECTIONS AND CLARIFICATIONS

Pathways of Discovery timeline: (11 Feb, p. 997). In the timeline accompanying David Stevenson's Pathways of Discovery essay, the main charge leading to the burning of Giordano Bruno was his denial of the divinity of Christ; his scientific views, however, didn't help. The timeline was prepared by the editors, not the essay's author.

Report: "Rapid evolution of a geographic cline in size in an introduced fly" by R. B. Huey *et al.* (14 Jan., p. 308). An arithmetical error was made in the computation of the divergence rate of North American *Drosophila*. The rate given in darwins was correct; however, the rate reported in haldanes was wrong. The correct values are 0.011 haldanes for females (penultimate paragraph of the text) and 0.004 haldanes for males (in reference 24). This error does not affect any major conclusion of the paper.

News Focus: "Baedeker's guide, or just plain 'trouble'?" by Michael Balter (7 Jan., p. 29). The caption accompanying the photo misidentified the actor in the role of King Solomon. The actor was Tyrone Power, not Yul Brynner. Power died during the shooting of the movie *Solomon and Sheba* in 1958 and was replaced by Brynner.

Editorial: "Avoiding an oil crunch" by Philip H. Abelson (1 Oct. 1999, p. 47). The reference to *Oil & Gas Journal* was incomplete. The reference should have been *Oil Gas J.* **97**, 26 (21 June 1999).