



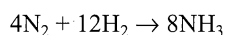
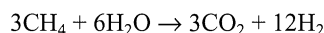
POLICY FORUM: CARBON AND AGRICULTURE

Carbon Sequestration in Soils

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Maintaining and increasing soil organic matter (SOM) adds to soil fertility, water retention, and crop production. Recently, many soil scientists have suggested that the sequestration of atmospheric carbon dioxide in SOM could also contribute significantly to attempts to adhere to the Kyoto Protocol. Conversion of large areas of cropland to conservation tillage, including no-till practices, during the next 30 years could sequester all the CO₂ emitted from agricultural activities and up to 1% of today's fossil fuel emissions in the United States (1). Similarly, alternative management of agricultural soils in Europe could potentially provide a sink for about 0.8% of the world's current CO₂ release from fossil fuel combustion (2). Beyond conservation tillage, however, many of the techniques recommended to increase carbon sequestration in soils contain hidden carbon "costs" in terms of greater emissions of CO₂ into the atmosphere.

Application of nitrogen fertilizer is often recommended to increase SOM, particularly on lands that have already experienced significant losses in SOM as a result of cultivation (3). At 100% efficiency, the stoichiometry of the Haber-Bosch process for the industrial production of ammonia indicates an emission of 0.375 moles of C per mole of N produced:



Ismail *et al.* (4) found a sequestration of 1250 grams of carbon per square meter (gC/m²) in soils under conventional tillage, and 1740 gC/m² under no-till practices in Kentucky, during 20 years of continuous cultivation of corn receiving nitrogen fertilizer at an annual rate of 336 kg/ha. However, the CO₂ released during the production of the fertilizer was equivalent to 334 gC/m², or 19 to 27% of the carbon sequestration (5). Additional carbon emissions are incurred in the manufacture, transport, and application of fertilizer. A factor of 1.436 moles of CO₂-C released per mole of N more accurately reflects the full carbon cost of N fertilizer (6). This

factor would effectively negate any net carbon sink as a result of the application of the fertilizer.

Increasing the production of plants on marginal, semiarid lands is another method frequently proffered to increase the storage of carbon in soils. In most cases, increasing plant production on these lands will require irrigation, yet irrigation is potentially associated with large CO₂ emissions. The fossil fuel-derived energy used in pumping irrigation water amounts to 22 to 83 gC/m² per year for irrigated lands in the United States (7). This emission is likely to exceed any net carbon sequestration on irrigated agricultural lands. Moreover, groundwaters of arid regions often contain as much as 1% dissolved Ca and CO₂ versus 0.036% in the atmosphere (8). When such waters are applied to arid lands, CO₃ is released to the atmosphere and CaCO₃ precipitates:



For example, taking the water-use efficiency of arid-land plants as 1428 g of H₂O lost per gram of biomass produced (9) and assuming a 50% C content in plant tissue, 0.042 gC is released as CO₂ per gram of C fixed in plant biomass. Thus, if irrigation water containing dissolved Ca at 50 mg/liter is used to increase plant production by 200 gC/m² per year on semiarid land, the net CO₂ released from the formation of soil carbonate would be 8.4 gC/m² per year. If only 1% of added plant production contributes to long-term carbon sequestration in the soil (10), irrigation actually transfers CO₂ from soils to the atmosphere.

Plants grown under high CO₂ concentrations use water more efficiently. Many workers have thus suggested that plant production and soil carbon storage may increase as the concentration of CO₂ rises in Earth's atmosphere. Wood *et al.* (11), using free-air CO₂ enrichment (FACE) technology on arid agricultural lands in Arizona, reported small increases in soil organic carbon as a result of the growth of cotton under high CO₂ concentrations. On their wet plot treatments, application of ~1.0 m of irrigation water (12), likely containing Ca concentrations as high as 50 mg/liter, would annually release 15 gC/m² to the atmosphere from the formation of pedogenic carbonate.

Applications of manure are often assumed to increase carbon sequestration in soils (2), but manure is not likely to yield a net sink for carbon in SOM. Buyanovsky and Wagner (13) showed that SOM increased with increasing C input from residues and manure in the Sanborn plots in Missouri. Manure was applied at an annual rate of 1340 g/m² to fields of corn and wheat. The highest levels of production were for corn, up to 1100 g/m² per year. If all of this crop were used for silage, and assuming the digestion efficiency of livestock is 60% (14), then the production of manure would be 440 g/m². Thus, the entire above-ground plant production on 3.0 ha of land was required to supply the manure to each hectare of manured land. Greater concentrations of SOM in manured fields can thus be expected to be associated with declining SOM on a proportionally larger area of off-site lands. Manuring has a number of practical applications, but net carbon sequestration is not one of them.

A substantial sink for carbon in soils may derive from the application of conservation tillage and the regrowth of native vegetation on abandoned agricultural land. Applications of fertilizer, irrigation, and manuring are important agricultural practices, but we should not be overzealous in estimating their contributions to the Kyoto Protocol. Treaty negotiators must keep in mind the complexities of a full accounting of the carbon emissions and sinks associated with various human activities.

References and Notes

1. J. S. Kern and M. G. Johnson, *Soil Sci. Soc. Am. J.* **57**, 200 (1993).
2. P. Smith *et al.*, *Global Change Biol.* **3**, 67 (1997).
3. P. E. Rasmussen and C. R. Rohde, *Soil Sci. Soc. Am. J.* **52**, 1114 (1988).
4. I. Ismail, R. L. Blevins, W. W. Frye, *ibid.* **58**, 193 (1994).
5. A table containing this information resides at <http://www.sciencemag.org/feature/data/1042216.shl>
6. R. C. Izaurralde *et al.*, in *Management of Carbon Sequestration in Soil*, R. Lal *et al.*, Eds. (CRC Press, Boca Raton, FL), pp. 433–446. The Intergovernmental Panel on Climate Change recommends a factor of 0.58 for the manufacturing process alone [Revised 1996 Guidelines for National Greenhouse Gas Inventories, Reference Manual, Organization for Economic Cooperation and Development, Washington, DC (1996)].
7. A. C. Morris, thesis, Princeton University (1999); R. J. Maddigan, W. S. Chern, C. G. Rizy, *Am. J. Agr. Econ.* **64**, 673 (1982).
8. W. W. Wood and M. J. Petraitis, *Water Resour. Res.* **20**, 1193 (1984).
9. R. A. Fischer and N. C. Turner, *Annu. Rev. Plant Physiol.* **29**, 277 (1978).
10. W. H. Schlesinger, *Nature* **343**, 232 (1990).
11. C. W. Wood *et al.*, *Agr. Forest Meteorol.* **70**, 103 (1994).
12. J. R. Mauney *et al.*, *ibid.*, p. 49.
13. G. A. Buyanovsky and G. H. Wagner, *Biol. Fert. Soils* **27**, 242 (1998).
14. National Research Council, *Nutrient Requirements of Beef Cattle* (National Academy of Sciences, Washington, DC, ed. 7, 1996).
15. This paper was prepared while I was a visiting professor at the California Institute of Technology.

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