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 CO_2 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 CO_2 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 CO_2 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:

$$3CH_4 + 6H_2O \rightarrow 3CO_2 + 12H_2$$

$$4N_2 + 12H_2 \rightarrow 8NH_3$$

Ismail *et al.* (*4*) found a sequestration of 1250 grams of carbon per square meter (gC/m^2) in soils under conventional tillage, and 1740 gC/m^2 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 CO_2 released during the production of the fertilizer was equivalent to 334 gC/m^2, 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 CO_2-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 CO_2 emissions. The fossil fuel–derived energy used in pumping irrigation water amounts to 22 to 83 gC/m^2 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 CO_2 versus 0.036% in the atmosphere (*8*). When such waters are applied to arid lands, CO_3 is released to the atmosphere and $CaCO_3$ precipitates:

$$Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3\downarrow + H_2O + CO_2\uparrow$$

For example, taking the water-use efficiency of arid-land plants as 1428 g of H_2O lost per gram of biomass produced (*9*) and assuming a 50% C content in plant tissue, 0.042 gC is released as CO_2 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/m^2 per year on semiarid land, the net CO_2 released from the formation of soil carbonate would be 8.4 gC/m^2 per year. If only 1% of added plant production contributes to long-term carbon sequestration in the soil (*10*), irrigation actually transfers CO_2 from soils to the atmosphere.

Plants grown under high CO_2 concentrations use water more efficiently. Many workers have thus suggested that plant production and soil carbon storage may increase as the concentration of CO_2 rises in Earth's atmosphere. Wood *et al.* (*11*), using free-air CO_2 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 CO_2 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/m^2 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/m^2 to fields of corn and wheat. The highest levels of production were for corn, up to 1100 g/m^2 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/m^2. 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.

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References and Notes

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15. This paper was prepared while I was a visiting professor at the California Institute of Technology.