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Agricultural Practices and Policies for Carbon Sequestration in Soil

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CHAPTER 23

Application of a Management Decision Aid for Sequestration of Carbon and Nitrogen in Soil

Alan Olness, Dian Lopez, Jason Cordes, Colin Sweeney, Neil Mattson, and W. B. Voorhees

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INTRODUCTION

Carbon (C) sequestration in agricultural lands will require complex management of soil. The U.S. Cornbelt is one of the major areas of potential C sequestration in agricultural soils. This region has about 53 million hectares of land under cultivation annually (Table 23.1; USDA-NASS, 1999). This represents about a third of all cropland in the U.S. In the early years of management, most farms had cattle, pasture, and forage production and this allowed farmers to rotate their crops. Today, much of the land is under annual crop production with some type of tillage to aid seedbed preparation and weed control. Tillage accelerates oxidation of soil organic matter and releases organically bound carbon, nitrogen (N), phosphorus, and sulfur (Schlesinger, 1986; Houghton, 1995; Lal, 1997; Reicosky, et al., 2000). Thus, soils are continually being mined of mineral nutrition for grain and oilseed crop production. In order to successfully sequester C in soil, careful management and co-sequestration of several elements are also essential. Nitrogen is the nutrient most often limiting crop production; it is also the element, aside from C, that is needed in the greatest amounts for C sequestration.

In the 1800s, much of the C and N in crops was recycled within the farm unit. However, over time, export of grain has been removing an increasing percentage of fixed C from the cycle. Today nearly 50% of the C fixed annually is removed and proposals are continually being made to remove an even larger fraction. This exportation removes C from the pool of material exploited by resident biology and gradually removes organic C from use by soil organisms. Today's crop production also exports even larger proportions of N from the agricultural landscape.

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Table 23.1 Average Crop Acreage Planted to Corn, Oat, Soybean, and Small Grains (per 1,000 ha) in the U.S. Corn Belt during 1996 to 1998

State	Maize	Soybean	Wheat	Other Grain	Total
Illinois	4,425	4,128	546	58	9,157
Indiana	2,334	2,219	304	27	4,883
Iowa	5,045	4,115	16	121	9,296
Kansas	1,113	944	4,573	80	6,710
Michigan	998	731	244	79	2,053
Minnesota	2,941	2,631	21	356	5,949
Missouri	221	1,902	553	15	2,692
North Dakota	337	479	30	1,230	2,076
Ohio	1,396	1,788	510	62	3,756
South Dakota	1,578	1,275	695	238	3,786
Wisconsin	1,545	420	60	250	2,274
Total	21,933	20,630	7,553	2,516	52,632

Note: Recompiled from USDA-NASS Agricultural Statistics, 1999.

Figure 23.1 A native prairie site on the Great Plains.

Most soil C comes from root mass. However, under natural conditions (Figure 23.1), above-ground biomass is continuously added to the surface mat of dead vegetation, which decays gradually. Rodents and other burrowing animals continuously till the soil and bury a portion of the above-ground biomass. This tillage is temporally and spatially diffuse, but effective in incorporating some aerial plant material into the soil. Under natural conditions, plants are usually N-limited and the C:N ratios of root and above-ground portions are quite large. Seeds and leaves, which generally have lesser C:N ratios, are quickly consumed, the carbohydrate and protein are extracted, and the more resistant material is returned as feces and gradually incorporated into the soil.

Agriculture tends to use plants with a smaller fraction of roots than native plants (Table 23.2). As root systems increase in protein content or fineness, they decay more rapidly and, as a consequence of smaller root fractions and greater ease of decay, the content of soil organic C decreases. Fertilization with N further decreases the root:shoot and root C:N ratios (Geisler and Krutzfeldt, 1984, cited by Klepper, 1991) and drives the system to greater and greater removal of fixed C as CO_2.

Natural systems are often both water- and N-limited. Soil texture (clay content) plus organic matter determines the range of soil water contents between –33 and –1500 kPa suction; this, plus

Table 23.2 Selected Root:Shoot Ratios and Total Plant Production for Selected Species

Environment	Root:Shoot Ratio	Total Aerial Biomass (g m^{-2})	Total Root Carbon (g m^{-2})	Reference	
Agriculture					
Cotton, annual	0.18	972[a]	70[a]	De Souza and Vieira Da Silva	1987
Cotton, perennial	0.49	972[a]	190[a]	with data from Mullins et al.	1990
Barley	0.1			Anderson–Taylor and Marshall	1983
Barley	0.28 to 0.60			Geisler and Krutzfeldt 1984 as recalculated by Klepper	1991
Wheat	0.09 to 0.12			Barraclough	1984
Bean	0.23 to 0.56			Geisler and Krutzfeldt 1984 as recalculated by Klepper	1991
Maize	0.18 to 0.92			Geisler and Krutzfeldt 1984 as recalculated by Klepper	1991
Maize	0.09	1370	130	Foth	1962
Maize	0.21[c]	1740[c]	<152	Balesdent and Balabane	1996
Native Plant					
Sideoats grama	0.35 to 0.60[b]	1080	80 to 130[b]	Kiniry et al.	1999
Switchgrass	0.30 to 0.73[b]	6210	380 to 930[b]	Kiniry et al.	
Eastern gamagrass	0.62 to 0.81[b]	2610	470 to 710[b]	Kiniry et al.	
Big bluestem	0.53 to 0.83[b]	2040	300 to 460[b]	Kiniry et al.	

[a] Assumed 16.2 plants m^{-2} with total mature plant dry weight of 60 g $plant^{-1}$.
[b] Determined at the end of the second season of growth.
[c] Constructed from the data.

the net difference between rainfall and evaporation, is the water available for crop production. Under natural conditions a small amount of N is received in rainfall, which is about equal to the amounts lost as ammonia or through denitrification. Thus, because C fixation depends largely on N supply, the largest amounts of N in natural soil organic matter are contributed through fixation by symbiotic microorganisms. With continuous plant cover, soils remain cooler, microbial decay of soil organic matter proceeds gradually, and organic N is continuously taken up by the new vegetation. Little N is lost through leaching events.

THE DELICATE BALANCE

The accumulation of soil organic C is the result of a delicate balance between C fixation and microbial decay of senescent vegetation (mainly root mass). Productivity, or carbon fixation, of any site depends on availability of water and nitrogen. The decay of organic matter is described by a negative general energy model for limited systems, GEMLS (Olness et al, 1998):

$$Y_t = Y_o(b - ((e^{k(t-to)} - e^{-k(t-to)})/(e^{k(t-to)} + e^{-k(t-to)})))$$

in which

Y_t = the amount of organic carbon remaining at any time, t
t = time (a substitute expression for internal energy relationships of microbial decay)
Y_o = the amount of organic carbon originally added
k = the time coefficient (a composite of all other energy forms, affecting the system; for example, oxygen, water, other nutrition, etc.)
t_o = that time at which the decay begins (in this case $t_o = 0$), and b = a resistant base level coefficient (here assumed to be zero)

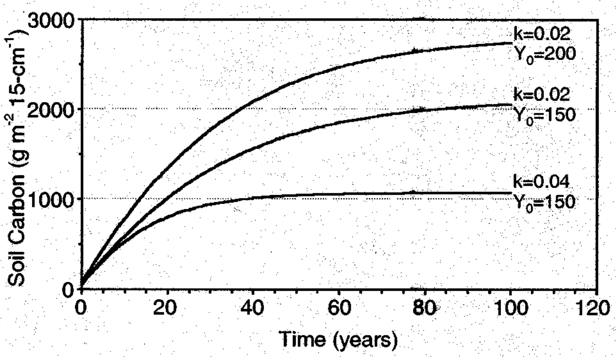

Figure 23.2 Accumulation of C in soil as a function of the time coefficient or decay rate, k, the amount of C in root biomass, and time.

Typical time coefficients range between 0.01 to 0.1 (ignore, for the moment, multicompartment models; see Molina et al., 1980). Using representative data from Table 23.2 and integrating the decay model over time, a relative accumulation of soil organic matter (Figure 23.2) can be described. One of the consequences of decay models is the achievement of some maximal equilibrium concentration of C in soil. As the decay constant increases, this limit is reached more rapidly; in the case of $k = 0.04$ and $Y_o = 150$ g biomass (60 g of C), the limit is nearly reached in 40 years. As the decay coefficient decreases, the time required to approach equilibrium increases and the amount of C accumulated increases. Decay models generally predict that the largest increases in soil C occur early (20 to 40 years) within a restoration period. Thus a key to C sequestration in soil is managing the rate of decay of soil organic matter.

An accumulation of 2 kg of C m^{-2} 15-cm^{-1} depth increment with a soil bulk density of 1.0 g cm^{-3} will effect a C concentration of about 1.33%. Soil organic C contents of three to four times this amount are common in native prairies. This suggests that root masses of native prairie were much larger than those reported in Table 23.2, the decay constants are smaller than 0.02, or above-ground biomass was incorporated into the soil, or some combination of the above. Perennial grasses, for which root mass lives for several years, could effect an apparent decay constant of less than 0.02.

Once established in the soil, the equilibrium organic C levels are lost through increasing the decay constant. In this regard, tillage is a major factor in soil C loss. With tillage, C fixation in soil is interrupted, often for 2 to 3 months at a time (Figure 23.3). Soil microbial activity, however, continues and is often accelerated because the insulating effect of plant residues has been removed and soil temperatures are increased. With continued mineralization comes production of nitrates easily leached from the soil profile or, in the case of saturated conditions, eliminated through denitrification.

FACTORS OF SOIL CARBON SEQUESTRATION AND DEVELOPMENT OF A MODEL

Five major abiotic factors affect mineralization of soil organic matter (Olness et al., 1998): clay content, soil pH, soil bulk density, rainfall (water balance), and temperature (Figure 23.4). The first four factors affect soil aeration or oxygen supply; temperature is perhaps the most important factor in that it can be manipulated by cultural practice. The general effect of temperature on biological activity is shown in Figure 23.4. While any number of biological data sets show the same general nature of the relationship, the data were extracted from Blacklow (1972) for maize roots and fit with a GEMLS model. Manipulation of temperatures greater than about 30°C or less than about 9°C have little effect on biological activity. However, in the range of 9 to 30°C, a change in soil temperature has an important effect on relative biological respiration.

Figure 23.3 A site similar to that in Figure 23.1 after fall cultivation. Photograph taken in the spring.

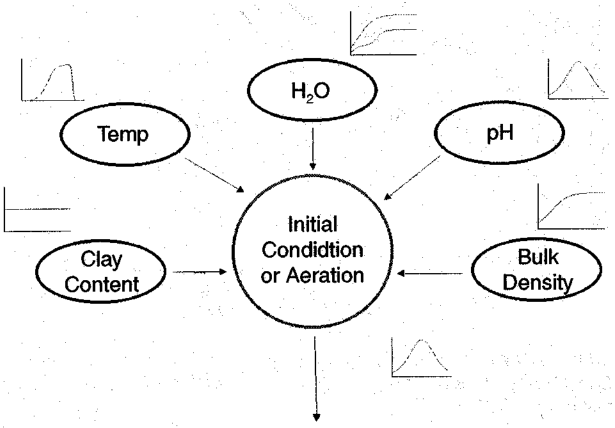

Figure 23.4 The five main factors affecting soil microbial production of nitrate–nitrogen in soil. Mathematical descriptions of these factors are integrated into the USDA-ARS nitrogen fertilizer decision aid.

The effect of soil aeration on microbial activity was well described by Skopp et al. (1990) as a delicate balance between having sufficient water for substrate diffusion and microbial movement and adequate oxygen for respiration. This balance is illustrated as a combination of two opposing GEMLS (Figure 23.5), using data obtained by Doran et al. (1990). Microbial respiration is maximized when water-filled pore space ranges from about 50 to 75%. The sensitive ranges for respiration are water-filled pore spaces < 50 and > 75%, but these ranges are of little value to cultivated agriculture (paddy culture excluded). Thus, manipulation of water would seem to offer less opportunity for control of respiration than that of temperature.

Soil water-filled pore space is a function of soil water content and is largely controlled by soil clay content (texture) and soil organic matter content (see also Hudson, 1994). In this situation, two supplemental GEMLS functions provide a reasonable description of the effects of soil clay content and soil organic matter content on the total water-holding capacity of the soil. (The models were developed using data [not shown] from Olson, 1970; Figure 23.6.)

The other factor needed to determine soil water-filled pore space is total soil porosity or soil bulk density. Along with the combination of texture and clay content, it determines relative soil

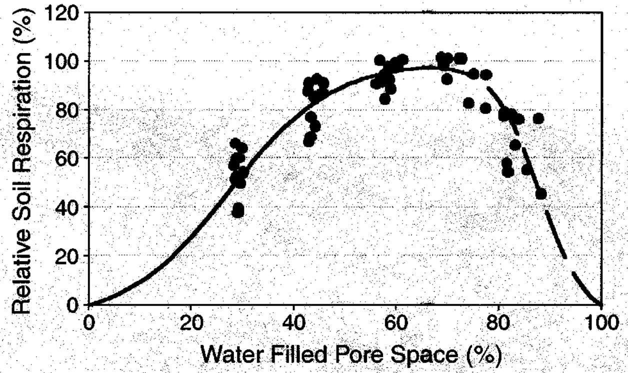

Figure 23.5 Relative microbial respiration as a function of water-filled pore space. Data from Doran et al., 1990, and modeled using two opposing GEMLS.

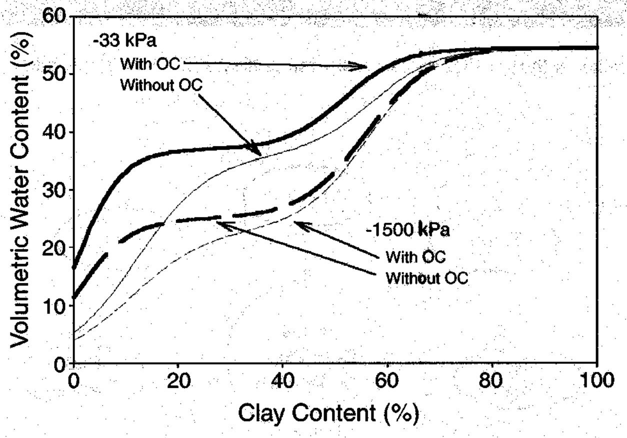

Figure 23.6 Soil volumetric water content at field capacity (–33 kPa) and permanent wilting point (–1500 kPa) as a function of clay content and organic matter. Data from Olson, 1970, and modeled using two supplementary GEMLS.

aeration, which controls soil microbial respiration. When these factors are combined, we can see how complex interactions affect respiration (microbial oxidation) and mineralization of soil organic matter (Figure 23.7). Many native prairie soils have bulk densities of about 1.0, which tends to be too well aerated (too dry) for optimal microbial respiration; this aids accumulation of soil organic C. For many soils, a bulk density of about 1.2 is achieved at planting; this tends to be ideal for microbial mineralization of organic matter. It is no coincidence that crop producers are taking advantage of the mineralization of soil organic matter as a source of N for crop production. Interestingly, in the initial years of conversion to no-tillage, a bulk density of 1.4 is common for medium textured soils, but this tends to be too wet for maximal microbial activity. The common observance is that no-tilled soils tend to be N deficient relative to tilled soils. This slowed N production rate is a measure of the potential conserving ability of no-tillage to sequester C and N.

Soil pH (hydrogen ion activity) controls microbial enzymatic efficiency (Olness, 1999). Organic N is mineralized and nitrified most rapidly at a pH optimum of about 6.7 (Figure 23.8). This observation suggests that both hydroxyl and hydrogen ions are inhibitors of microbial respiration. Liming acid soils or additions of ammoniacal fertilizers effects an acceleration of microbial decay of soil organic matter due simply to the change in hydroxyl or hydrogen ion concentrations.

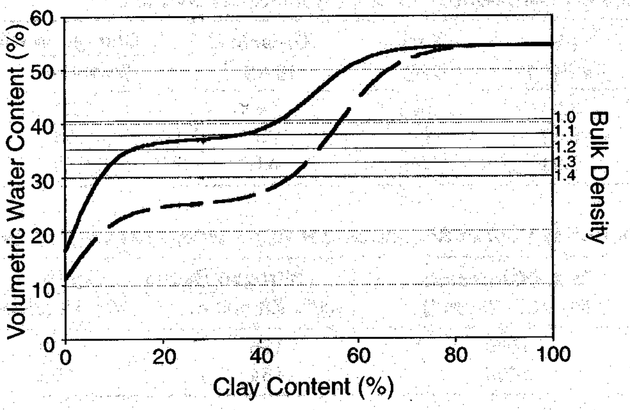

Figure 23.7 The effect of soil bulk density and volumetric water content on water-filled pore space. The intersection between the horizontal bulk density line with the field capacity curve gives water-filled pore space optimal for maximal microbial respiration. Modified from Olness et al., 1997.

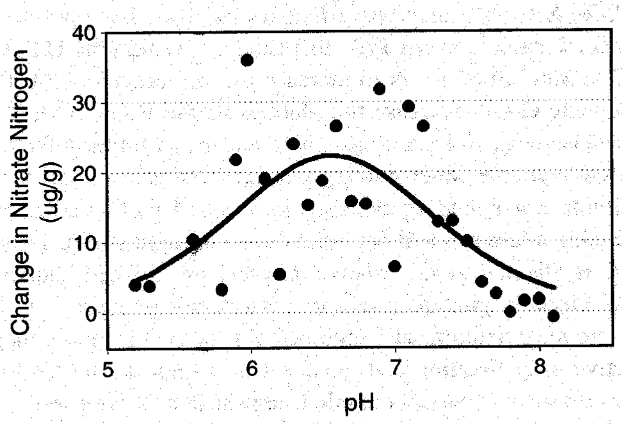

Figure 23.8 The general effect of pH on change in nitrate–N concentration in the upper 30 cm of soil. Reprinted with permission; Olness et al., 1997 (see further, Olness, 1999).

NITROGEN: THE SUBTLE COST OF SOIL CARBON SEQUESTRATION

Nitrate formation in soil is a very sensitive measure of soil microbial respiration as long as leaching is taken into account or prohibited. By combining the abiotic factors, a model of activity can be constructed. When this is done, rather close agreement between observed and predicted nitrate formation is obtained (Table 23.3). The model seems to accommodate a range of soil pH values, soil textures and organic matter contents. A production of 10 μg N g^{-1} of soil in the upper 60 cm of the profile in a 60-day period equals about 80 kg of N converted from organic amine to mineral nitrate-N. Because soil C:N ratios vary in a narrow range around 10.0, a reliable estimate is that about 800 kg of C ha^{-1} were digested and most likely lost as CO_2.

This brings us to a critical aspect of C sequestration in soil. Soil organic matter contains about 9% N, with some additional phosphorus and sulfur. In order to aid C sequestration, a source of N must be sacrificed or stored with the C. The opportunity cost of storing this C in terms of N is shown in Table 23.4. A conservative estimate yields a cost of 136 to 164 kg of N ha^{-1} needed to increase soil organic C by 0.1% if the C:N ratio is 11.0 and the system is 100% efficient with the

Table 23.3 Prediction of Changes in Soil Nitrate-N Concentration

	pH ($g\ kg^{-1}$)	Clay ($g\ kg^{-1}$)	Organic C ($g\ kg^{-1}$)	Change in Nitrate-N ($\mu g\ kg^{-1}$)	
				Observed	Predicted
Minimum	5.81	242	14.1	–0.58	0.81
Mean	6.53	311	20.2	5.68	2.37
Maximum	7.91	373	44.7	11.70	10.7

Table 23.4 Opportunity Cost of Sequestered N Required to Increase Soil Organic C by 0.1%

Bulk Density ($Mg\ m^{-3}$)	Total OC Increase ($kg\ ha^{-1}\ 15\text{-}cm^{-1}$)	Nitrogen Required[a] ($kg\ ha^{-1}$)		Cost[b] ($\$\ ha^{-1}$)
		100% Efficiency	50% Efficiency	
1.0	1500	136	272	52 → 104
1.2	1800	164	328	63 → 126

[a] Assumed C:N ratio of 11.0.

[b] Assumed cost of N = $ .386 kg^{-1}.

N. The value of this N can be reasonably estimated from current market prices at about \$52 to \$63 ha^{-1}. Nitrogen use efficiency is rarely 100%; literature citations usually quote a range of efficiencies from < 40 to about 75%. Assuming an N use efficiency of 50%, the opportunity cost of N required to increase soil C by 0.1% rises to about \$104 to \$126 ha^{-1}. Within the U.S. Corn Belt, this would amount to about \$27 to \$66 billion for N to increase the soil organic C by 1%.

Increasing soil organic C will increase the plant available water content of the soil (Hudson, 1994), which will increase crop yield in areas where water is a limiting factor in crop production. However, the increased available water-holding capacity varies with soil texture. Also, the value of the increased available water-holding capacity, in terms of yield, varies with the climatic zone and likelihood of realizing a loss of yield potential due to drought stress. Thus the opportunity cost of N in sequestered C is affected by the relative recovery of cost with increased yield of crops.

These costs for N virtually guarantee that increasing soil organic C will have to be effected initially through symbiotic N fixation with legumes. As the soil N status increases, legumes tend to become less effective in N_2 fixation and grasses tend to invade the landscape. At present, the most likely candidates for increasing soil organic C appear to be alfalfa (*Medicago sativa* L.), hairy vetch (*Villa vilossa* L.), or, perhaps, woody legumes because of their ability to fix prodigious amounts of N. The latter would seem to be less compatible with current crop production.

CONCLUSIONS

Extensive agricultural production of U.S. soils with tillage encourages continuous mining of soil organic C and release of N. Additionally, grain crops often have lesser root production than native perennial grasses; this further encourages depletion of soil organic C. Decay models predict that the amount of C that can be sequestered in the soil has some natural limit that depends on the type of plant grown as well as five abiotic factors.

The abiotic factors are soil clay content, soil bulk density, soil pH, soil water content, and temperature. Of these factors, manipulation of temperature would seem to offer the most effective means of increasing soil organic C, which will have the beneficial effect of increasing water available for crop production; this will partially offset the cost of increasing C. Manipulations of soil bulk density, aeration, or soil pH are less reasonable alternatives for aiding sequestration of C.

Because soil organic matter has a C:N ratio of about 11, sequestration of soil organic C will require an opportunity cost of N. This cost is estimated to range from \$27 to \$66 billion for each 1% increase in soil C in the U.S. Corn Belt. Symbiotic fixation of N_2 through use of legumes seems the most likely cost-effective means of achieving this N input.

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