Soil Organic Matter

General Characteristics of Soil Organic Matter

Influences chemical and physical properties of soil in far greater proportion than amount found in soil

- Has water holding capacity 4-5 times greater than clay
- Reservoir for some nutrients
- Accounts for at least 1/3 of total CEC
- Contributes strongly to soil aggregation and stability

Extremely active on a weight basis

General Characteristics of Soil Organic Matter

Soil OM is composed of organic material in various stages of decomposition

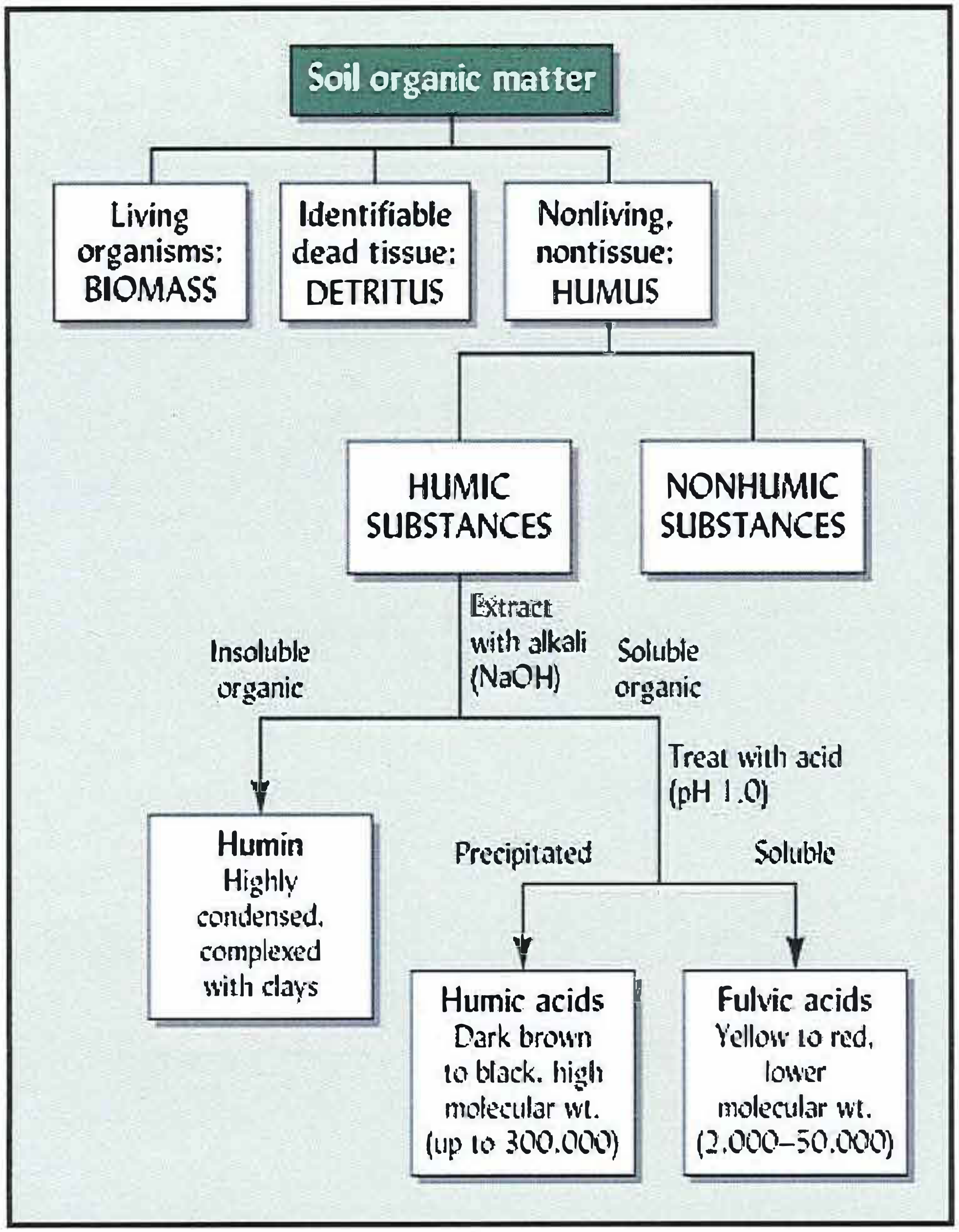
- <u>Fresh plant residues</u> are primary source
  - Leaves, stems, roots
- <u>Products of decomposition reactions</u>
  - Simple inorganic products *oxidized* like N, S, P, CO_2
  - *Mineralization* reactions produce Ca^{2+}, Mg^{2+}, K^+
- <u>Humus or humic substances</u>

Humus: Genesis and Nature

Humus: heterogeneous mixture of complex organic substances no longer identifiable as tissues

2 general groups of compounds comprise humus

- Humic group
  - Fulvic acid fraction
  - Humic acid fraction
  - Humin
- Non-humic group



Soil Organic Matter Components

Humic Substances: *Humic Group*

Fulvic acid fraction

- Relatively easy to decompose (15-20 years)
- Soluble in both acid and alkaline substances
- Relatively low molecular weight

Humic acid fraction

- Relatively difficult to decompose (100's of years)
- Alkali soluble only (pH of solute >7)
- Medium molecular weight

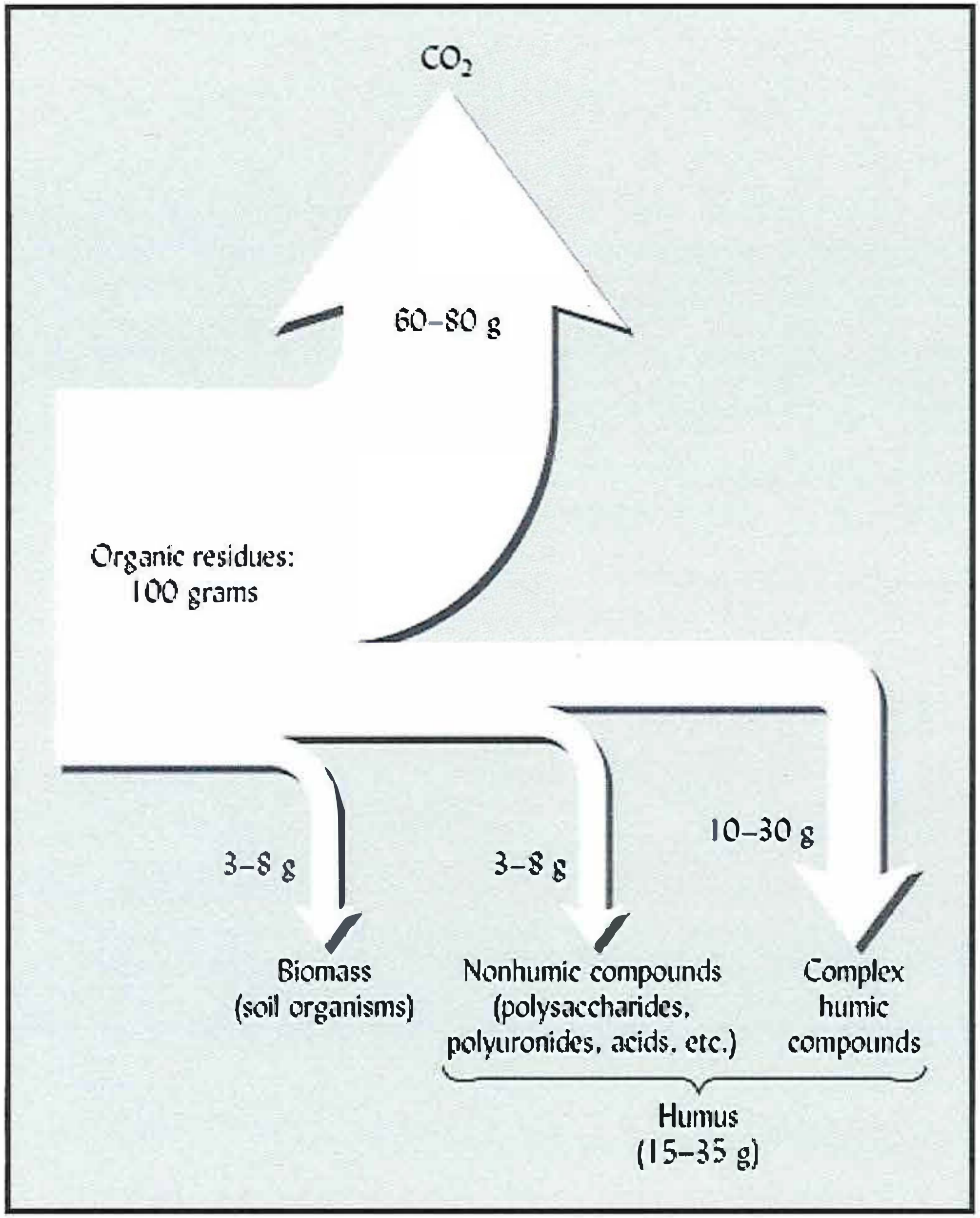
Humic Substances: *Humic Group*

Humin

- Very difficult to ever decompose
- Insoluble in anything
- High molecular weight

Humic Substances: *Non-humic Group*

- Comprises 20-30% of the organic matter in soils
- Less resistant to decomposition by microbes
- Includes polysaccharides
- May interact with humic group on occasion



Typical Fates of 100 Grams of Organic Residues 1 Year After Incorporation

Summary of Steps in Formation of Organic Matter

Addition of organic residues to soil

Breakdown of plant and animal residues

Synthesis of new compounds

Mineralization of nutrients

Polymerization into humus

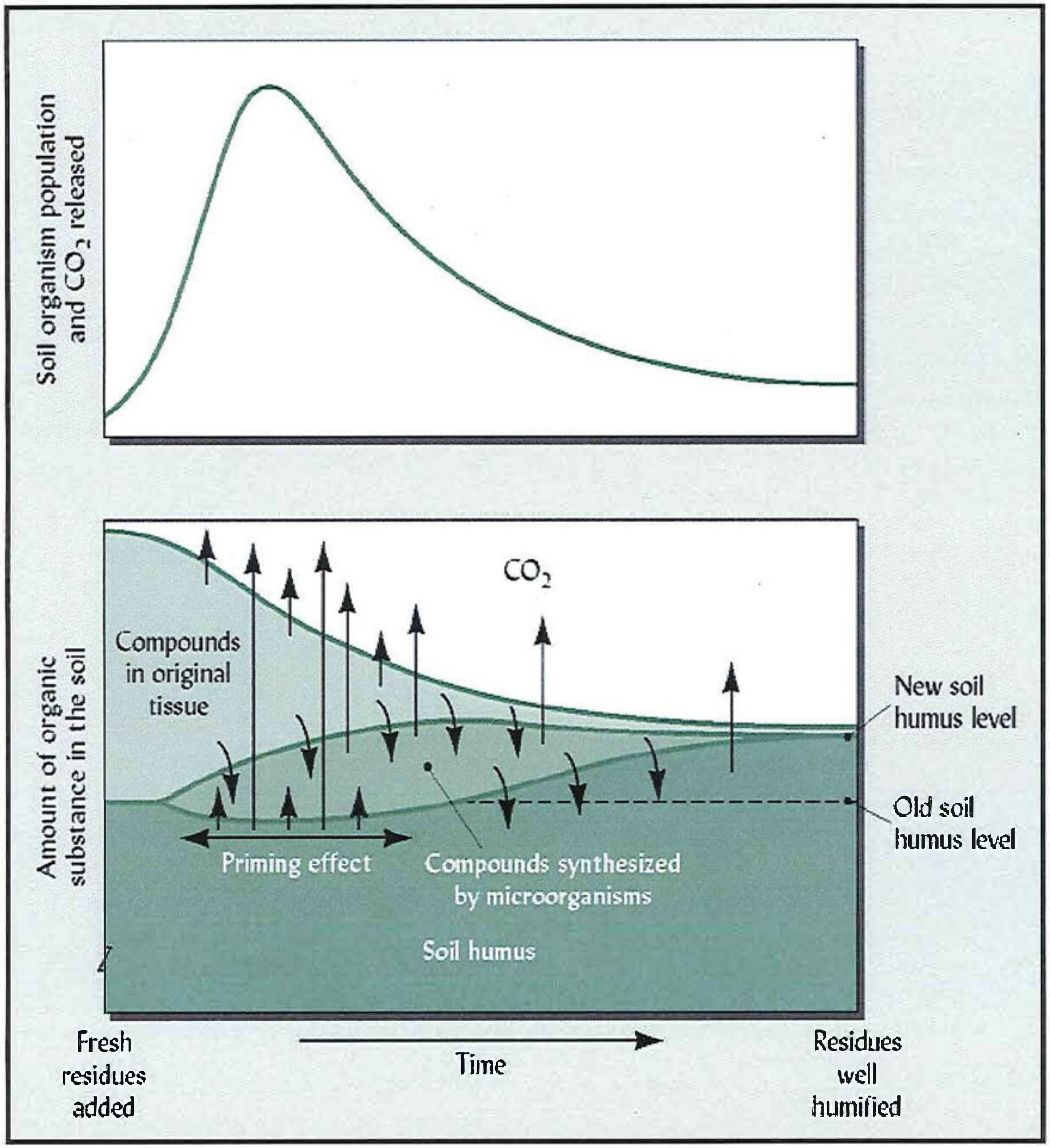


Diagram of general changes which take effect as fresh residues are added to a soil. Arrows indicate transfers of Carbon. Most C released as CO_2 but some is synthesized by microbes into compounds which will eventually become humus.

Conditions Affecting OM Concentration in Soils

Generally, OM concentration is <u>increased</u> by:

1. Decreasing temperatures
   - High temperatures cause decomposition to outstrip production

2. Increasing rainfall

3. Finer textures (silts and clays vs. sands)
   - Can hold more moisture, produce more material, maintain optimum soil temperatures better

Conditions Affecting OM Concentration in Soils

Specifically, OM concentration is <u>increased</u> by:

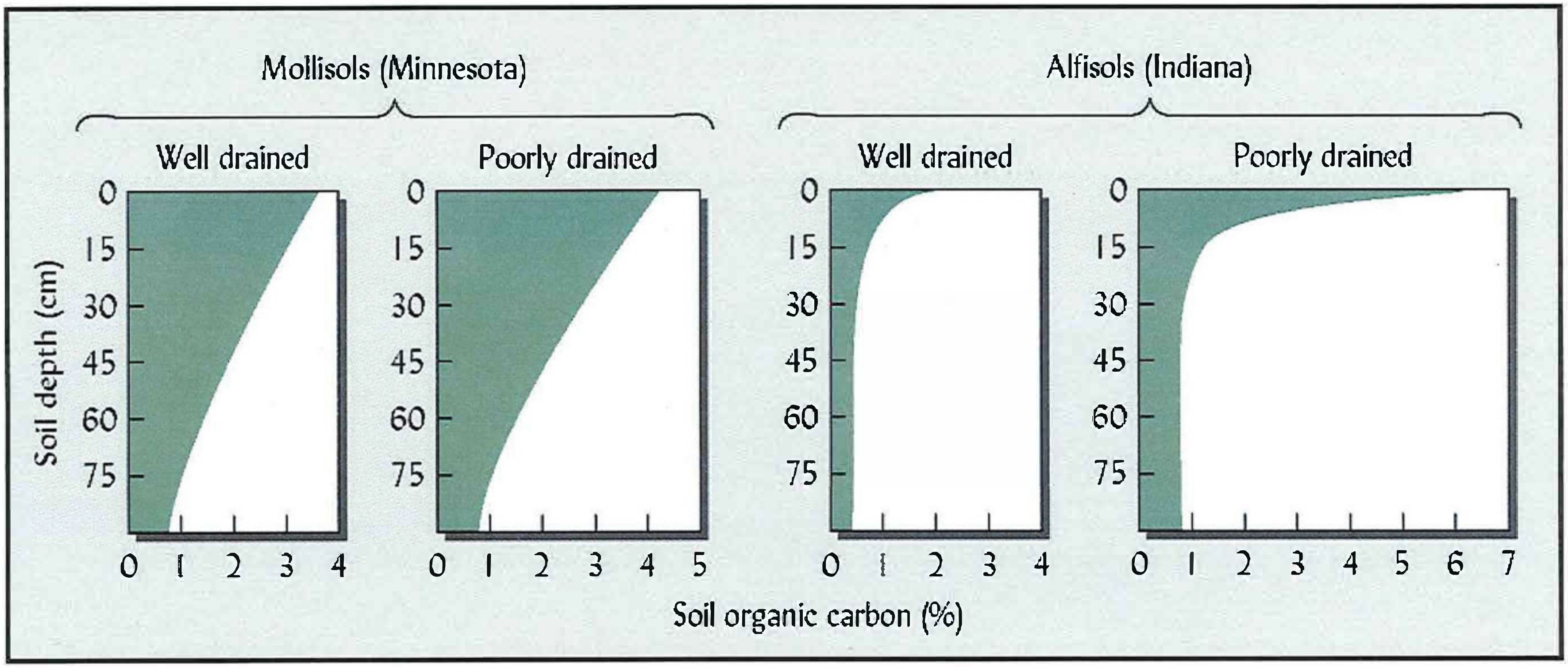
1. Lesser aeration, (poorly drained soils)
   - Residues can't decompose as rapidly
2. Adding larger quantities of carbon and nitrogen
   - Crop rotations with legumes, adding manures, fertilizers
3. Adequate soil fertility
   - Helps increase amounts of residue produced

Conditions Affecting OM Concentration in Soils

Specifically, OM concentration is *decreased* by:

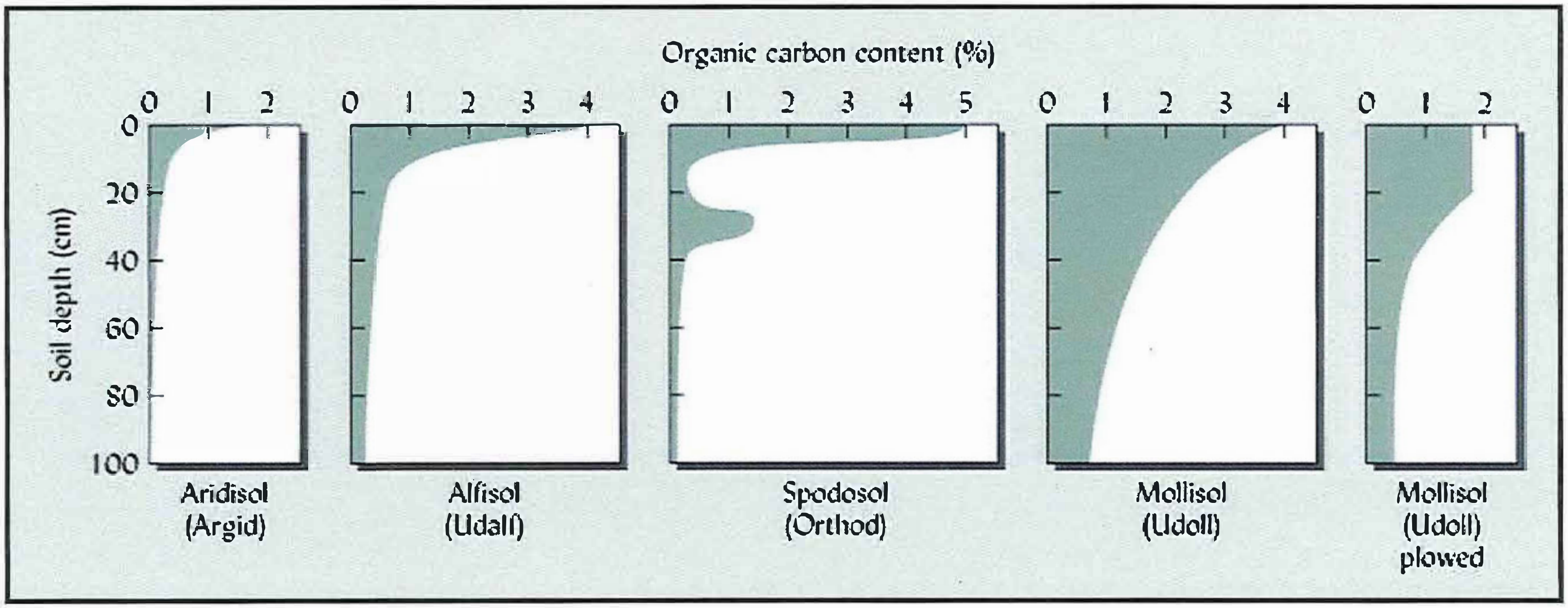
- Tillage and drainage
  - Tillage breaks up organic residues and brings them into contact with decomposing organisms or with air (volatilization can occur)
  - Drainage improves environment for decomposing microorganisms
- Low yielding crops (less OM returned to soil)
- Mining soil fertility (removing nutrients w/out replacing)
  - Especially Nitrogen as it governs C:N ratio

Distribution of Organic Carbon in Poorly and Well Drained Soil Profiles



Note that poor drainage results in higher organic carbon content

Vertical Distribution of Organic Carbon in Well Drained Soils in Different Soil Orders



Note the higher organic carbon in the grassland soils (Mollisols) compared to the others

Importance of Nitrogen to OM

Carbon makes up largest part of organic matter, but Nitrogen is also present

- The amount of Carbon to Nitrogen present in a given soil is called the **C:N ratio**
- This ratio is important because it…
  - Indicates the amount of plant available Nitrogen
  - Controls the total amount of soil organic matter
  - Determines the rate of decay of organic matter
  - Helps in managing soils

C:N Ratio (Carbon:Nitrogen Ratio)

When organic matter containing Carbon and Nitrogen is added to soil, microorganisms multiply rapidly producing CO_2

- CO_2 is produced using a majority of the carbon in the residue
- Nitrogen in the residue is used to build microorganism tissues (their 'body')
- Therefore, **Carbon is used and Nitrogen is conserved**

C:N Ratio (Carbon:Nitrogen Ratio)

As residues decompose, they release carbon (CO_2) to bring the C:N ratio back to 10:1

- Stable OM has C:N ratio of 10:1
- Ratio varies by residue type
  - Grasses: 50-100:1
  - Legumes: 15-25:1

- Variable ratio means there is little free N available in soils with large amounts of grassy/woody residue

Direct Effects of OM on Plant Growth

Most benefits to plants come from the effect of organic matter on soil properties

- Majority of plant nutrients are not from OM
  - However, a small amount of N and P can be obtained by plants from organic compounds
  - Vitamins and other plant growth-enhancing substances can be obtained from products of OM decay
  - *Allelopathic chemicals* present in plant residue can inhibit growth of other plants

Influence of OM on Soil Physical Properties

Many soil properties and processes are influenced by OM or humic fractions including:

- *Colors* from dark brown to black
- *Aggregate stability and granular structure*
- *Reduced plasticity, cohesion and stickiness*
- *Increased infiltration rate and water holding capacity*

Influence of OM on Soil Chemical Properties

In mineral soils, humus or humic substances account for:

- 50 to 90% of the soil's cation-adsorbing power
- Significant amounts of nutrient cations
- Much of the soil's pH buffering capacity
- Holding N, P, S and some micronutrients as constituents of OM
- Increasing the decomposition of soil minerals

Management of High OM Soils

Applies particularly to Histosols or Histic subgroups

- Drainage leads to decomposition of OM
- Drying creates a very fine, erodible surface soil
  - Susceptible to wind erosion
- pH must be maintained at lower levels (pH 5.5)
  - Prevents chelation of micronutrients (binding of micronutrients by OM making them plant **unavailable**)
  - Prevents weed control problems

Soil organic matter (SOM) is necessary for all soil functions, and it is the most important indicator of soil health. It is the organic component of soil. It consists of varying proportions of small plant residue (fresh), small living soil organisms, decomposing (active) organic matter, and stable organic matter (humus) in varying stages (fig. 1). SOM is a mineralizable source of nutrients for crops. It increases the availability of most nutrients, buffers the effects of high acidity, increases the available water capacity and moisture retention of the soil, helps to minimize compaction and surface crusting, increases water infiltration, provides food for micro-organisms that facilitate the availability of nutrients, holds soil aggregates together, decomposes pesticides, and acts as a carbon sink.

The content of SOM can be estimated in the field and/or in a lab. The results can be used to estimate the amount of mineralized nitrogen, phosphorus, and sulfur available for crop production, which is needed to determine the appropriate application of fertilizers. As SOM increases, the buffering capacity of the soil also increases. Thus, the amount of surface-applied herbicides needed to effectively control weeds increases, the potential for herbicide carryover for future crops decreases, and the amount of lime needed to raise pH increases.

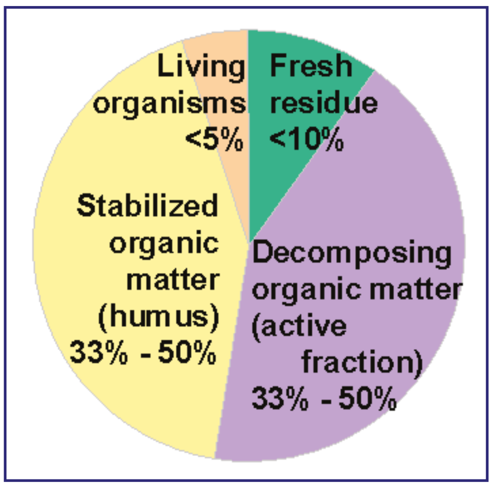


Figure 1.—Major components of soil organic matter (Source: Soil Food Web; USDA, NRCS).

Inherent Factors Affecting Soil Organic Matter

Inherent factors affecting soil organic matter include climate and soil texture and clay mineralogy. Climatic conditions, such as rainfall and temperature, and soil moisture and aeration (oxygen levels) affect the rate of organic matter decomposition. Organic matter decomposes faster in warm, humid climates and slower in cool, dry climates. It also decomposes faster when the soil is well aerated (higher oxygen level) and much slower when the soil is saturated (lower oxygen level). Decomposition is maximized when the soil is tilled, providing optimal oxygen for microbial activity. For more information, refer to figure 2 in the "Soil Respiration" guide for educators.

Soils that support grass vegetation (prairie) commonly have at least twice as much organic matter as those that support forest vegetation. Both the top growth and roots of grass vegetation dies continually each growing season, adding organic matter to the upper part of the soil. Soils that support forest vegetation commonly have relatively low organic matter content as a result of the following:

1. Trees produce a much smaller root mass per acre than do grasses.
2. Trees do not die back and decompose annually. Much of the organic matter in a forest is tied up in the wood of the trees and thus is not returned to the soil.

Figure 2 is a general map of the soil organic matter distribution across the United States. The darker the area, the higher the organic matter content.

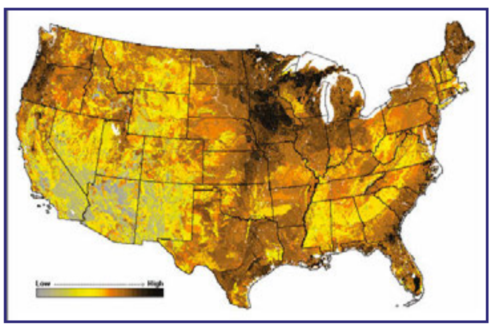


Figure 2.—Soil organic matter content (from the SSURGO database [USDA, NRCS]).

Soil Organic Matter Management

Under a given set of site conditions, SOM generally is highest in areas where soil disturbance is minimized, biomass production is higher, and organic material is added to the soil. Plant residue that has a low C:N ratio (high nitrogen content) decomposes more quickly than residue with a high C:N ratio, and it does not increase the content of SOM as quickly. Excessive tillage destroys soil aggregates, increasing the rate of decomposition of SOM. Stable soil aggregates have a higher content of active organic matter with less rapid microbial decomposition. Measures that increase soil moisture and temperature and optimize aeration accelerate the decomposition of SOM.

Management practices can either degrade or increase SOM. Some key practices that can help to increase or maintain the content of SOM are:

- *Using cropping systems* that incorporate continuous no-till, cover crops, solid manure or other organic material, and diverse rotations that include high-residue crops and perennial legumes or grasses.
- *Minimizing or eliminating tillage* that results in microbial activity, increasing the rate of organic matter decomposition and the risk of erosion.
- *Minimizing erosion*, which helps to maintain the content of SOM. Most SOM is in the upper part of the soil; thus, the content is reduced when the soil erodes.
- *Properly fertilizing* according to results of soil tests. Proper fertilization encourages the growth of plants. Root and top growth can help to increase or maintain the content of SOM, even if much of the top growth is removed.
- *Using perennial forage plants* to provide for annual dieback and regrowth of perennial grasses. The fibrous root systems of perennial grasses are particularly effective as a binding agent in soil aggregation. The extensive root systems and biomass of perennial forage plants also contribute organic matter to the soil.

Relationship of Soil Organic Matter to Soil Functions

Under average conditions in temperate regions, approximately 1.5 percent of SOM mineralizes annually (2 percent for spring-planted row crops, 1 percent for small grain, and 0.5 percent for perennial grass; Ray Ward, 2012) and the content of SOM can be maintained at current levels in soils that have 2 to 5 percent SOM (Doran, 2012). Mineralization rates and loss of SOM can increase dramatically under certain temperature, aeration, and moisture conditions.

Key soil functions for which SOM is needed include:

- *Nutrient supply.*—When SOM decomposes, nutrients are released and are available for plant use. Each percentage of SOM in the upper 6 inches (15.2 cm) of a medium textured soil (silt or loam with a bulk density of 1.2) releases about 10 to 20 pounds of nitrogen, 1 to 2 pounds of phosphorus, and 0.4 to 0.8 pounds of sulfur per acre per year. SOM maintains a supply of many nutrients for plant use (if the soil is not too acid), minimizes leaching of nutrients, and increases the availability of some nutrients.
- *Available water capacity*.—Organic matter acts similarly to a sponge. It can absorb and hold as much as 90 percent of its weight in water. Organic matter also releases nearly all of its stored water for plant use. In contrast, clay holds high quantities of water but much of it is unavailable to plants.
- *Soil aggregation*.—Organic matter contributes to soil aggregation, which improves soil structure. Better soil structure increases the infiltration of water through the soil and improves the ability of the soil to take in and hold water.
- *Erosion*.—Because SOM increases water infiltration and stabilizes soil aggregates, the risk of erosion is minimized.
- *Soil carbon retention*.—Stabilized SOM sequesters atmospheric carbon. If continued SOM-enhancing management practices are used, the amount of CO_2 released in the atmosphere is minimized.

Estimating the amount of organic material needed to increase SOM:

The term **steady state** refers to the condition in which the amount of organic matter added from crop residue, roots, and manure or other organic material equals the rate of decomposition. If the amount of organic matter added is less than the rate of decomposition, the content of SOM will decline. Conversely, if the amount of organic matter added is higher than the rate of decomposition, the content of SOM will increase.

An acre of soil 6 inches (15.2 cm) thick weighs approximately 2,000,000 pounds. One percent SOM, therefore, weighs about 20,000 pounds (dry). Under normal conditions, 10 pounds of organic material decompose into about 1 pound of organic matter. Thus, at least 200,000 pounds (100 tons) of organic material must be applied or returned to the acre of soil to produce 1 percent stable organic matter ("What Does Organic Matter Do In Soil?"; Funderburg, 2001; Samuel Roberts Noble Foundation).

What management practices are being used that will affect soil organic matter?

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What impact will these practices have on soil organic matter? Why?

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Measuring Soil Organic Matter

Materials needed to measure soil organic matter:

____ Soil color chart for estimating organic matter content.

____ Plastic container and probe for gathering and mixing soil samples.

____ Squirt bottle of water to moisten soil if it is dry.

____ Pen, field notebook, permanent marker, and resealable plastic bags.

Considerations:

Soil organic matter typically is measured in a lab. The University of Illinois soil color chart can be used to estimate the amount of SOM in mineral soils that support grass. The chart can also be used to estimate SOM in other soils that have a dark-colored surface layer, but the estimate for these soils is not as accurate. Instructions for use of the color chart are provided with the chart. Other accepted methods for estimating SOM, such as use of color charts for other types of soils and laboratory tests, can also be used.

In-field estimate of soil organic matter content (refer to color chart instructions for additional guidance):

1. *Soil sampling.*—Soil organic matter is highly variable. At least 10 small samples to a depth of 8 inches or less (if tilled) are gathered randomly from an area that represents a particular soil type and management history. By observing color changes in a soil profile, it may be determined that the samples can extend to a shallower depth in areas of continuous no-till cropland, grassland, and forestland. Place samples in the small plastic container and mix. If desired, the SOM for each sample can be estimated separately and then averaged for the entire area. Repeat step 1 for each sampling area.
2. *Use moist soil with a broken aggregate face*.—If the soil sample is dry, moisten it. Match the soil color to the color chart (fig. 3). Record the associated organic matter content given in table 3, and complete the calculations in the interpretations section of this guide.

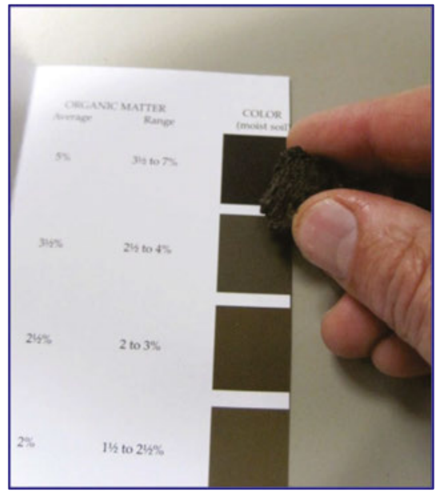

Figure 3.—Soil color chart matched to soil that contains 3.5 percent soil organic matter (Kucera, 2012).

Interpretations

Record SOM content. Estimate the amount of organic material, carbon (C), nitrogen (N), phosphorus (P), and sulfur (S) in the SOM. Estimate the average annual mineralization of N, P, and S. Using the information in tables 1 and 2 and the example calculations that follow, complete table 3. Compare management systems. Answer discussion questions.

Table 1.—Ratio of carbon, nitrogen, phosphorus, and sulfur and average mineralization factor in soil organic matter (Doran, 2012).

Ratio, percentage, and factor	Carbon	Nitrogen	Phosphorus	Sulfur
Ratio in soil organic matter	100	10	1	0.25-0.50
Ratio of carbon to element	1:1	10:1	100:1	200-400:1 (average 300:1)
Percentage of soil organic matter	58 percent	5.8 percent	0.58 percent	0.15-0.29 percent (average 0.22 percent)
Annual mineralization factor (may need to be adjusted for local conditions)	1.5 percent under normal temperate conditions (0.015 factor)			

Table 2.—Average bulk density for organic matter and soil textures (Rawls, 1983).

Organic matter and textures	Average bulk density (g/cm^3)
Organic matter	0.22
Sand	1.56
Loamy sand	1.54
Sandy loam	1.50
Loam	1.45
Silt loam	1.20
Sandy clay loam	1.63
Silty clay	1.55
Clay loam	1.45
Silty clay loam	1.40
Red clayey soils	1.10
Soils that formed in volcanic ash	0.80

Soil organic matter calculations (depth in metric units converted to depth in pounds/acre):

Follow example to complete table 3. Estimate total C, N, P and S, and average annual nutrient (N, P, and S) release from soil organic matter (dominantly stable and active SOM fractions). Adjust sampling depth as appropriate.

Example—

Silty clay loam, 8-inch (20.3-centimeter) sample depth; estimated 2 percent organic matter by comparing to soil color chart; no bulk density (BD) measurement (BD based on average values given in table 2).

Sampling depth conversion:

Sampling depth in centimeters (cm) = inches (in) x (2.54). For example, 8 in (sampling depth) x 2.54 = 20.3 cm sampling depth

Estimated bulk density calculation (refer to “Bulk Density” guide for educators for calculating actual bulk density or use estimates from table 2 in this guide):

$$\text{Estimated bulk density (table 2)} = \frac{100}{(\%\text{ organic matter} \div \text{organic matter BD}) + (100 - \%\text{ organic matter} \div \text{average soil BD})}$$

$$\frac{100}{(2 \div 0.22\ g/cm3) + ([100 - 2] \div 1.40\ g/cm3)} = 1.26 \text{ grams per cubic centimeter (g/cm3)}$$

Soil organic matter (SOM) (lbs/ac-depth): (Soil organic matter percentage x 10,000 parts per million [ppm]) x (bulk density) x (sample depth [cm] ÷ 10) x (0.893 [conversion factor])

For example, (2 % x 10,000 ppm) x (1.26) x (20.3 cm ÷ 10) x (0.893) = 45,682 lbs SOM/ac-8 in.

Soil organic carbon (C) (lbs/ac-8 in): 45,682 lbs SOM/ac-8 in x 0.58 (58 percent organic C) = 26,496 lbs organic C/ac-8 in.

Soil organic nitrogen (N) (lbs/ac-8 in): 45,682 lbs SOM/ac-8 in x 0.058 (5.8 percent organic N) = 2,650 lbs organic N/ac-8 in.

Mineralized organic nitrogen (N) (lbs/ac-8 in/yr): 2,650 lbs organic N x 0.015 (mineralization factor) = 39.8 lbs mineralized organic N/ac-8 in.

Soil organic phosphorus (P) (lbs/ac-8 in): 45,682 lbs SOM/ac-8 in x 0.0058 (0.58 percent organic P) = 265 lbs organic P/ac-8 in.

Mineralized organic phosphorus (P) (lbs/ac-8 in/yr): 265 lbs organic P x 0.015 (mineralization factor) = 4.0 lbs mineralized organic P/ac-8 in.

Soil organic sulfur (S) (lbs/ac-8 in): 45,682 lbs SOM/ac-8 in x 0.0022 (0.22 percent organic S) = 100.5 lbs organic S/ac-8 in.

Mineralized organic sulfur (S) (lbs/ac-8 in/yr): 100.5 lbs organic S/ac-8 in x 0.015 (mineralization factor) = 1.5 lbs mineralized organic S/ac-8 in.

Table 3.—Soil organic matter calculations
(Adjust calculations based on sampling depth.)

Site	Sample depth (cm)	SOM (%)	Bulk density (g/cm3)	Soil organic matter (lbs/ac)	Soil organic C (lbs/ac)	Soil organic N (lbs/ac)	Miner-alized organic N (lbs/ac/yr) (excludes N flush from wetting of dry soil)*	Soil organic P (lbs/ac)	Miner-alized organic P (lbs/ac/yr)	Soil organic S (lbs/ac)	Miner-alized organic S (lbs/ac/yr)
Ex.	20.3	2	1.26	45,682	26,496	2,650	39.8*	265	4.0	100.5	1.5

*More accurate estimates of yearly organic N release can be estimated by measuring N released from active and microbial organic matter in soil because of rewetting of dry soils. In the example, an additional 20 to 30 lbs/ac of N can be released from micro-organisms (N flush) as a result of soil wetting and drying. This additional N flush can be estimated using the Solvita® test (see “Soil Respiration” guide for educators) or using a biological respiration and nitrification test, which is available at soil testing laboratories.

Are SOM levels expected to decline, improve, or remain the same? Why?

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Do total soil organic matter content, nutrients contained in soil organic matter, and nutrients mineralized annually appear to be too high or too low? Why or why not?

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Glossary

Active organic matter.—Organic compounds used as food by micro-organisms and associated with high biological activity. Active soil organic matter breaks down faster than other components of soil organic matter and responds more quickly to changes in management.

Fresh residue.—Plant residue, dead animals, and other organic substances that have recently been added to the soil and exhibit minimal decay.

Humus (stable organic matter).—Complex organic compounds that remain after organisms have used and transformed the original organic material. Humus is not readily decomposed either because it is physically protected inside soil aggregates or it is chemically too complex to be used by most organisms. Humus is important in binding soil aggregates and improves the water and nutrient-holding capacity of soils.

Mineralization.—Organic matter decomposition that releases nutrients in a form available for plants (e.g., phosphorus, nitrogen, and sulfur).

Soil micro-organisms (small living organisms).—Bacteria, fungi, nematodes, protozoa, and arthropods, etc.

Soil organic matter (SOM)–Organic component of soil, consisting of plant residue (fresh), living organisms, decomposing organic matter (active), and stable organic matter (humus).

Soil Quality Indicators: Organic Matter

USDA Natural Resources Conservation Service **April 1996**

What is soil organic matter?

Soil organic matter is that fraction of the soil composed of anything that once lived. It includes plant and animal remains in various stages of decomposition, cells and tissues of soil organisms, and substances from plant roots and soil microbes. Well-decomposed organic matter forms *humus*, a dark brown, porous, spongy material that has a pleasant, earthy smell. In most soils, the organic matter accounts for less than about 5% of the volume.

What does organic matter do?

Organic matter is an essential component of soils because it:

- provides a carbon and energy source for soil microbes;
- stabilizes and holds soil particles together, thus reducing the hazard of erosion;
- aids the growth of crops by improving the soil's ability to store and transmit air and water;
- stores and supplies such nutrients as nitrogen, phosphorus, and sulfur, which are needed for the growth of plants and soil organisms;
- retains nutrients by providing cation-exchange and anion-exchange capacities;
- maintains soil in an uncompacted condition with lower bulk density;
- makes soil more friable, less sticky, and easier to work;
- retains carbon from the atmosphere and other sources;
- reduces the negative environmental effects of pesticides, heavy metals, and many other pollutants.

Soil organic matter also improves tilth in the surface horizons, reduces crusting, increases the rate of water infiltration, reduces runoff, and facilitates penetration of plant roots.

Where does it come from?

Plants produce organic compounds by using the energy of sunlight to combine carbon dioxide from the atmosphere with water from the soil. Soil organic matter is created by the cycling of these organic compounds in plants, animals, and microorganisms into the soil.

What happens to soil organic matter?

Soil organic matter can be lost through erosion. This process selectively detaches and transports particles on the soil surface that have the highest content of organic matter.

Soil organic matter is also utilized by soil microorganisms as energy and nutrients to support their own life processes. Some of the material is incorporated into the microbes, but most is released as carbon dioxide and water. Some nitrogen is released in gaseous form, but some is retained, along with most of the phosphorus and sulfur.

When soils are tilled, organic matter is decomposed faster because of changes in water, aeration, and temperature conditions. The amount of organic matter lost after clearing a wooded area or tilling native grassland varies according to the kind of soil, but most organic matter is lost within the first 10 years.

Rates of decomposition are very low at temperatures below 38 °F (4 °C) but rise steadily with increasing temperature to at least 102 °F (40 °C) and with water content until air becomes limiting. Losses are higher with aerobic decomposition (with oxygen) than with anaerobic decomposition (in excessively wet soils). Available nitrogen also promotes organic matter decomposition.

What controls the amount?

The amount of soil organic matter is controlled by a balance between additions of plant and animal materials and losses by decomposition. Both additions and losses are very strongly controlled by management activities.

The amount of water available for plant growth is the primary factor controlling the production of plant materials. Other major controls are air temperature and soil fertility. Salinity and chemical toxicities can also limit the production of plant biomass. Other controls are the intensity of sunlight, the content of carbon dioxide in the atmosphere, and relative humidity.

The proportion of the total plant biomass that reaches the soil as a source of organic matter depends largely on the amounts consumed by mammals and insects, destroyed by fire, or produced and harvested for human use.

Practices decreasing soil organic matter include those that:

1. **Decrease the production of plant materials by**
   - replacing perennial vegetation with short-season vegetation,
   - replacing mixed vegetation with monoculture crops,
   - introducing more aggressive but less productive species,
   - using cultivars with high harvest indices,
   - increasing the use of bare fallow.

2. **Decrease the supply of organic materials by**
   - burning forest, range, or crop residue,
   - grazing,
   - removing plant products.

3. **Increase decomposition by**
   - tillage,
   - drainage,
   - fertilization (especially with excess nitrogen).

Practices increasing soil organic matter include those that:

1. **Increase the production of plant materials by**
   - irrigation,
   - fertilization to increase plant biomass production,
   - use of cover crops
   - improved vegetative stands,
   - introduction of plants that produce more biomass,
   - reforestation,
   - restoration of grasslands.

2. **Increase supply of organic materials by**
   - protecting from fire,
   - using forage by grazing rather than by harvesting,
   - controlling insects and rodents,
   - applying animal manure or other carbon-rich wastes,
   - applying plant materials from other areas.

3. **Decrease decomposition by**
   - reducing or eliminating tillage,
   - keeping the soil saturated with water (although this may cause other problems),
   - keeping the soil cool with vegetative cover.

(Prepared by the National Soil Survey Center in cooperation with the Soil Quality Institute, NRCS, USDA, and the National Soil Tilth Laboratory, Agricultural Research Service, USDA). Animal waste photo courtesy University of Nebraska-Lincoln, Institute of Agriculture and Natural Resources

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Soil Quality Indicators

Particulate Organic Matter

Particulate organic matter (POM) fraction referred to in this document comprises all soil organic matter (SOM) particles less than 2 mm and greater than 0.053 mm in size (Cambardella and Elliot, 1992). POM is biologically and chemically active and is part of the labile (easily decomposable) pool of soil organic matter (SOM). Figure 1 shows tiny debris of POM (0.25 mm < POM size < 0.5 mm) at different stages of decomposition isolated from soil under no-till management. Studies have shown that POM accounts for few to large amounts of soil C (20% and more) in some soils of Eastern Canada and the USA depending upon agroecosystems and management practices (Table1).

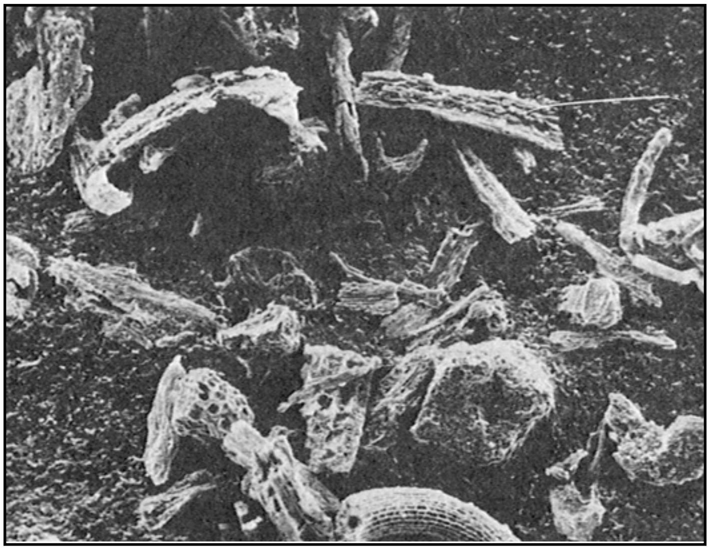

Figure 1. Particulate organic matter from no-till soil. From Cambardella and Elliot, 1992.

Factors Affecting

Inherent and dynamic soil properties and human activities that affect biomass production, accumulation, and/or decomposition will affect POM content in soils.

Inherent

Climactic conditions, such as rainfall and temperature, can affect the amount of plant biomass production and residues entering soil and thus POM accumulation in the soil. Soil types, especially soil texture, affect POM accumulation. For example, clay has a strong association with POM and serves as a physical barrier to microbial access, hence reducing microbial decomposition and increasing POM accumulation. Topography, especially elevation and slope, can create a gradient of POM distribution due to differences in temperature and vegetation types at different elevations and in erosion sensitivity on various slope classes.

Dynamic

The addition of plant residues or other organic amendments increase total organic carbon and its associated POM carbon (figs 2 and 3). Organic residues with a low C/N ratio (high nitrogen content) may decompose quickly and reduce the accumulation of POM. Soil disturbances such as destruction of aggregates by cultivation and alternating periods of wetting and drying expose organic matter to microbial decomposition and reduce POM content in soils. Stable soil aggregates promote POM buildup by protecting organic matter (OM) bound in and between aggregates from rapid microbial decomposition. However, adequate soil moisture and temperature, and aeration can accelerate the mineralization of SOM and its POM fraction.

Relationship to Soil Function

As perhaps the most easily decomposable fraction of non-living SOM after microbial biomass, POM fulfills many soil functions mediated by OM. It is a source of food/energy for microorganisms and soil animals as well as nutrients for plant growth. Particulate organic matter enhances aggregate stability, water infiltration and soil aeration; it increases cation exchange capacity and buffering pH. It also binds environmental pollutants such as heavy metals and pesticides. Particulate organic matter may play an important role in the suppression of soil borne diseases (e.g. damping off of cucumber) by compost. This may be explained by the fact that POM is an important source of food/energy in the compost for microorganisms responsible of disease suppression.

POM and Poor Soil Function

In poorly managed soils, the transport by erosion of sediments rich in POM into rivers and other water bodies can result in alteration of water quality and aquatic life. Build up and mineralization of those organic materials lead to the eutrophication of lakes and rivers. Incomplete mineralization of POM C in very poorly drained soils can lead to the formation of methane, which escapes into the atmosphere and contributes to ozone depletion.

Improving POM Levels

Management that affects SOM accumulation also affects POM content in soil (figs 2 and 3). More POM in the soil means that carbon and other nutrients are being stored in the intermediately available pool and are not subjected to losses (e.g., leaching) yet are available when needed. The following practices enhance POM levels:

- Tillage management (no-till, strip till, and ridge till)
- Crop rotation, cover crops, and cropping frequency (reduction in fallow frequency)
- Application of manure/compost and organic by-products
- Pasture and hay land management (e.g., rotational grazing and haying)

Measuring POM

There are several different laboratory methods to estimate POM and associated carbon. No reliable field methods exist yet. POM measurement in laboratory is time-consuming (1 to several days).

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Cambardella CA and Elliot ET. 1992. Particulate soil organic matter changes across a grassland cultivation sequence. Soil Sci Soc Am J 56:777-83.

Carter MR, Angers DA, Gregorich EG, and Bolinder MA. 2003. Characterizing organic matter retention for surface soils in eastern Canada using density and particle size fractions. Can J Soil Sci 83:11–23.

Fronning BE, Thelen KD, and Min D. 2008. Use of manure, compost, and cover crops to supplant crop residue carbon in corn stover removed cropping systems. Agron J 100:1703-10.

Table 1. Average C in whole soil, POM, percent POM-C (0-10 cm soil depth) from selected study sites in Eastern Canada. Adapted from Carter et al., 2002.

Site Name	Management	Whole Soil (C g/Soil kg)	POM (C g/Soil kg)	POM (%)
St. Rosalie	Cont. corn	30.2	8.2	22.5
La Pocatiere	Barley/clover	23.7	2.8	11.8
Normandie	Barley/clover	22.2	5.0	22.5
Nappan	Cont. grass	27.1	10.1	37.2
Benton	Potato rotation	20.3	12.1	12.0
Harrow	Corn/oats	21.5	2.7	12.5
St. Lambert	Cont. corn	22.3	3.9	17.5
Ottawa	Cont. corn	27.2	4.9	21.5
Chicott	Cont. corn	14.5	4.3	29.3
Harrington	Barley/soybean	21.2	2.8	10.8
Delhi	Corn/soybean/ grain/tobacco	7.6	1.4	18.4

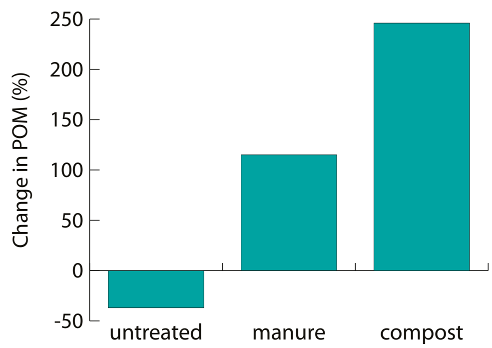

Figure 2. Effect of soil amendments on POM in crop soils. Adapted from Fronning et al., 2008.

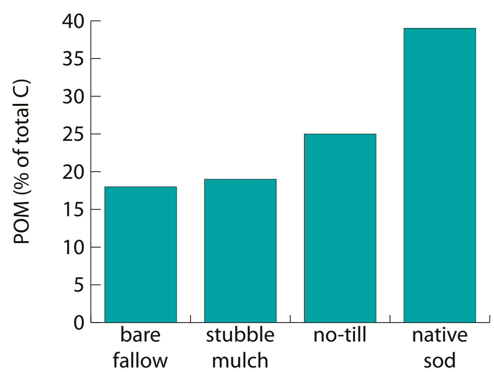

Figure 3. Effect of soil amendments on POM. Adapted from Cambardella and Elliot, 1992.

USDA United States Department of Agriculture

NRCS Natural Resources Conservation Service

Soil Quality Institute

Soil Quality Technical Note No. 5

Managing Soil Organic Matter

The Key to Air and Water Quality

Management

Reduced tillage, Cover crops, Rotational grazing, High biomass rotations

Soil quality

Soil organic matter, Soil structure, Soil Organisms, Water holding capacity, Infiltration

Air quality, Water quality, Productivity

Fewer pollutants, Less dust, Less sediment, Drought and disease resistance

Erosion control is not enough

Soil conservation policy in the United States stems from the devastating erosion events of the 1920s and ’30s. Out of concern for preserving agricultural productivity came the concept of tolerable soil loss and the creation of the T factor – the maximum annual soil loss that can occur on a particular soil while sustaining long-term agricultural productivity. Conservationists focused on reducing soil loss to T by applying practices, such as terraces, contour strips, grassed waterways, and residue management.

By the end of the century, concerns about air and water quality became as important as concerns about agricultural productivity. To address these environmental goals and maintain the land’s productive potential, we must now go beyond erosion control and manage for soil quality. How soil functions on every inch of a farm – not just in buffers or waterways – affects erosion rates, agricultural productivity, air quality, and water Soil organic matter, Soil quality. The most practical way to enhance soil quality today is to promote better management of soil organic matter or carbon. In short, we should go beyond T and manage for C (carbon).

Why focus on soil organic matter?

Many soil properties impact soil quality, but organic matter deserves special attention. It affects several critical soil functions, can be manipulated by land management practices, and is important in most agricultural settings across the country. Because organic matter enhances water and nutrient holding capacity and improves soil structure, managing for soil carbon can enhance productivity and environmental quality, and can reduce the severity and costs of natural phenomena, such as drought,flood, and disease. In addition, increasing soil organic matter levels can reduce atmospheric CO_2 levels that contribute to climate change.

Technical Note No. 5

October 2003

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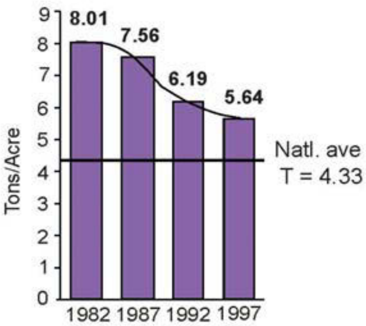

Figure 2: **National annual soil loss.**

The pace of erosion control has slowed as we approach the goal of managing to T. Annually, 1.8 billion tons of soil are still lost from cropland, and 120 million acres of cropland are eroding at a rate greater than T.

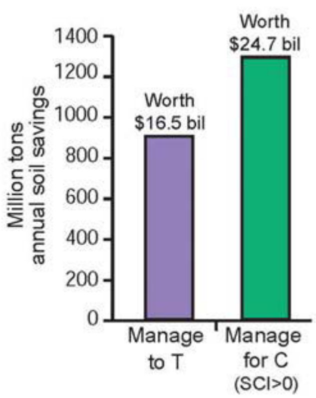

Figure 3: **Managing for soil organic matter can save more soil.**

If all cropland were managed to T, annual soil loss would decline by 0.85 billion tons. If all cropland were managed for C (SCI>0*), soil loss would decline by 1.29 billion tons. Thus, conservation efforts could save an additional $8.2 billion worth of soil annually by managing for C instead of managing to T. Reaching this higher standard is possible by focusing on different conservation tools and benefits.

Go beyond T– Manage for C

The goal of reducing soil erosion to T (tolerable soil loss rates) generated remarkable improvements in the nation's natural resources (figure 2). We can achieve a new level of soil conservation by focusing on building soil organic matter or soil carbon (C).

- By emphasizing organic matter management technology, soil loss can be reduced on those lands that still suffer excessive erosion.

- Even moderate erosion rates can harm air quality, water quality, and wildlife habitat. Improving soil organic matter levels can further stabilize soil within fields and protect environmental quality (figure 3).

- Keeping soil in place is only the beginning of soil conservation. Soil also has to function well. It must hold nitrogen, phosphorus, and pesticides in place and keep them out of surface water. Soil must deliver nutrients and water to plants as they need them. Soil should minimize the effects of floods and droughts. Organic matter helps soil perform all these functions.

What does this mean for conservation?

Managing for C means using well-known technology in a new way. By addressing conservation issues from the perspective of soil organic matter instead of erosion, we will focus on enhancing the soil as opposed to managing for tolerable degradation. We will exploit the full potential of cover crops, crop rotations, and reduced tillage to address conservation concerns. Moreover, managing for C provides additional on-site benefits and incentives for the landowner, creating greater motivation for the person making the ultimate decisions about managing the Nation's natural resources.

Keeping soil in place is only the beginning of soil conservation. Soil also has to function well.

*What is SCI? The Soil Conditioning Index (SCI) predicts the effect of cropping systems on soil organic matter levels. A positive SCI indicates a cropping system that, if continued, is likely to result in increasing levels of soil organic matter. More information about the SCI is at http://soils.usda.gov/sqi.

How does organic matter work?

Once a land manager begins working towards enhancing soil organic matter, a series of soil changes and environmental benefits follow (figure 4). The rate and degree of these changes and the best suite of practices needed to achieve results vary with soil and climate. Initially, managing for greater soil organic matter may require higher pesticide, herbicide, or nutrient applications. In time, productivity and environmental quality will be enhanced.

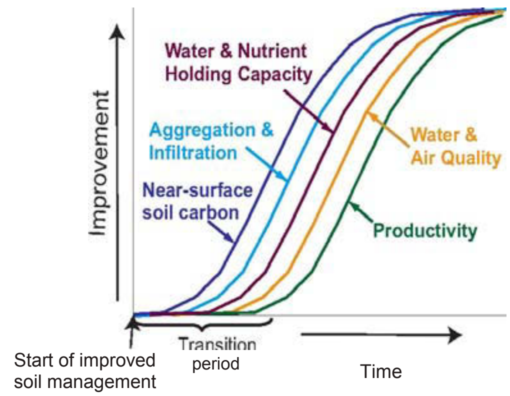

Figure 4: **Clean air and water start with soil organic matter**

Apply practices that enhance soil organic matter

- **Diverse, high biomass crop rotations**
- **Cover crops**
- **Reduced tillage**
- **Rotational grazing**

Organic matter dynamics change

- **Increased surface residue forms a physical barrier to wind and water erosion.**
- **Higher residue rotations and cover crops contribute more organic matter and nutrients to the soil.**
- **Less soil disturbance means lower organic matter losses.**

Soil properties change

- **Surface structure becomes more stable and less prone to crusting and erosion.**
- **Water infiltration increases and runoff decreases when soil structure improves.**
- **Soil organic matter holds 10 to 1,000 times more water and nutrients than the same amount of soil minerals.**
- **Beneficial soil organisms become more numerous and active with diverse crop rotations and higher organic matter levels.**

Air quality, water quality, and agricultural productivity improve

- **Dust, allergens, and pathogens in the air immediately decline.**
- **Sediment and nutrient loads decline in surface water as soon as soil aggregation increases and runoff decreases.**
- **Ground and surface water quality improve because better structure, infiltration, and biological activity make soil a more effective filter.**
- **Crops are better able to withstand drought when infiltration and water holding capacity increase.**
- **Organic matter may bind pesticides, making them less active. Soils managed for organic matter may suppress disease organisms, which could reduce pesticide needs.**
- **Crop health and vigor increase when soil biological activity and diversity increase.**
- **Wildlife habitat improves when residue management improves.**

What is topsoil worth?
Organic matter management is cost effective because it can prevent erosion and help remedy the effects of past erosion. Here are examples of how to put a dollar value on soil.

	Cost/ton
Cost by the bag	$40 - $80
Cost by the truckload	$15
Cost to replace soil functions, and remedy off-site damage (figure 5)	$19*
Cost of erosion to downstream navigation	$0 - $5
Cost to human health	$3
Cost to return soil to its original, noneroded condition	Priceless

Figure 5: **Components of the value of a ton of topsoil worth $19*.**

*Data are adjusted to 1997 dollars. For more detail see: NRCS. (draft). Soil Quality-Agronomy Technical Note. The economic value of soil quality. http://soils.usda.gov/sqi

National trends in soil organic matter management

The amount of cropland managed using methods that improve soil organic matter increased by 46 million acres between 1982 and 1997 (figure 6). An additional 48 million acres, formerly with degrading organic matter trends, were taken out of production. Organic matter levels can be improved without taking land out of agricultural production.

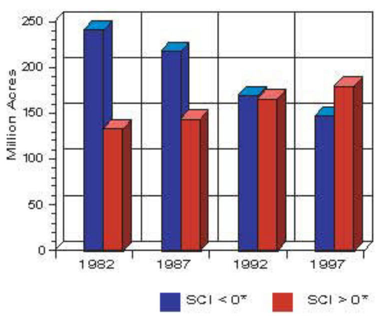

Figure 6: **Trends in soil organic matter management.**

* A positive SCI indicates a cropping system that, if continued, is likely to result in increasing levels of soil organic matter.

What can you do?

Go beyond T – Manage for C. Focus on management practices that build soil carbon and enhance soil function across the landscape. Practice standards important to organic matter management include:

- Conservation Crop Rotation (328)
- Cover Crop (340)
- Residue Management–Mulch Till, No Till, Strip Till, Ridge Till (329A-C)
- Prescribed Grazing (528) when used to improve the health and vigor of pasture plant communities and to improve soil condition.

In addition, appropriate irrigation technology may be important to increasing plant vigor and biomass production.

Expect a transition period and learning curve associated with management changes. Soil biological and physical properties will improve before increased soil organic matter is noticeable.

Avoid single-bullet solutions. No single practice works alone to enhance soil function, and no single set of practices works everywhere. Aim to improve soil organic matter and soil function, rather than to implement a particular set of practices.

Well-managed, continuous no till may be the most cost effective practice in many places, but even no till may not stand alone. No till should be combined with compaction prevention; a diverse, high-biomass rotation; and other locally relevant practices. In some areas, such as on wet and clayey soils, strip tillage or other variations are preferable.

Protect the investment. In many parts of the country, every tillage event can reduce soil organic matter. Occasional tillage can destroy all of the organic matter gained during several years of no till.

For more information about soil quality and soil organic matter, visit the NRCS Soil Quality Web site at http://soils.usda.gov/sqi.

Produced by the USDA Natural Resources Conservation Service http://www.nrcs.usda.gov.
The Natural Resources Conservation Service provides leadership in a partnership effort to help people conserve, maintain, and improve our natural resources and environment.

August 2003

Reactive Carbon

Soil organic matter (SOM) contains C compounds with different levels of degradability, from very easily decomposable to extremely resistant (recalcitrant) to decomposition. Each C component has a different residence time in the soil and performs different functions. Reactive carbon (RC), also known as permanganate oxidizable carbon (POxC), is a fraction of the SOM pool that is oxidizable in the presence of potassium permanganate in solution. Carbon oxidized by this compound includes the C most readily degradable by microorganisms as well as that bound to soil minerals, making RC interpretation somewhat difficult. Because of this association to the mineral fraction, RC is considered a chemical indicator, not a biological indicator. Nevertheless, a recent research project conducted across a range of environments and management conditions (12 studies) showed that POxC was significantly related to particulate organic carbon, soil microbial biomass carbon (BMC), and, in one study, soil organic carbon.

The residence time of RC is estimated to be 2 to 5 years, in contrast to recalcitrant C (e.g., humus) that has a turnover time of several hundred to thousands of years. Reactive carbon originates from the various fractions of SOM. These fractions include fresh organic material, soil microbial biomass, particulate organic matter, and other easily metabolized organic compounds, such as carbohydrates (sugars) and proteins (amino acids), as well as C loosely bound to soil minerals. Because of its relatively short turnover time, RC is more sensitive to management changes affecting soil C in agro-ecosystems than total organic carbon (TOC). Reactive carbon may be used as an indicator of change produced by cropping and soil management practices that manipulate SOM content.

Factors Affecting

Inherent — Soil climatic conditions (soil moisture and temperature) influence the mineralization rates of organic carbon and, concomitantly, the accumulation or decline of the quantity of RC in SOM. Clay minerals can strongly bind SOM and so protect that organic matter and the associated RC from rapid mineralization, whereas sand and silt are non-binding. Very poor drainage creates anaerobic conditions that favor the formation of methane (CH_4), inducing a systemic loss of carbon and decline in TOC and RC contents.

Dynamic — Figure 1 shows a significant positive relationship between TOC and RC, with POxC increasing with increasing TOC content, which occurred in one study. In recent studies however, the relationship was not so strong. Similarly, a positive relationship between RC, microbial biomass levels, and aggregate stability has been reported in the literature. The beneficial effect of SOM on aggregate formation is well established. These relationships may be due to the accumulation of carbon inside the aggregates, where it is protected from oxidation.

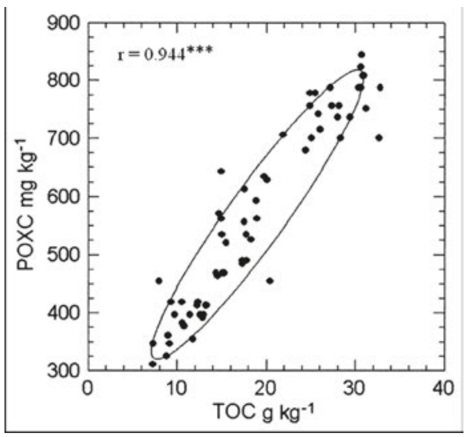

Figure 1. Relationship between total organic carbon (TOC) and permanganate oxidizable carbon (POXC) (adapted from Lucas and Weil, 2012).

Relationship to Soil Function

It is well documented that many soil functions are strongly influenced by SOM and, due to its association with TOC and microbial biomass, are likely to be related to RC as well. However, as the exact nature of the C fraction extracted by the potassium permanganate oxidation method has not been fully characterized, the functions affected must be addressed in general terms. Enhanced water aggregate stability by high levels of SOM (and, concomitantly, high levels of RC) improves water infiltration, reducing soil degradation by water and wind erosion. Reactive carbon is linked to a number of soil processes, including microbial biomass growth/activity and nutrient cycling. Researchers have found that POxC is significantly related to MBC and in few cases SOC and, thus, may be equally well suited to track management practices that promote C sequestration.

Problems with Poor Activity

Due to the relatively short turnover time of RC, significant decreases in RC may signal a decline in SOM and indicate the deterioration of physical, chemical, and biological properties and processes related to SOM. The adverse effects caused by the decline in RC include reduced aggregate stability, increased bulk density, and reduced water infiltration, water-holding capacity, microbial activity, and nutrient availability.

Improving Management

All practices that increase SOM will likely increase RC. Figure 2 shows changes in RC content under two different soil management practices. As expected, no-till (NT) resulted in a significant increase in SOM and RC when compared to conventional tillage (CT). Some practices beneficial for increasing SOM (and potentially RC) are:

- Reduced tillage (no-till);
- Adoption of crop rotations, cover crops, or other crop diversity measures;
- Addition of manure, fresh residues, and compost; or
- Combinations of the above.

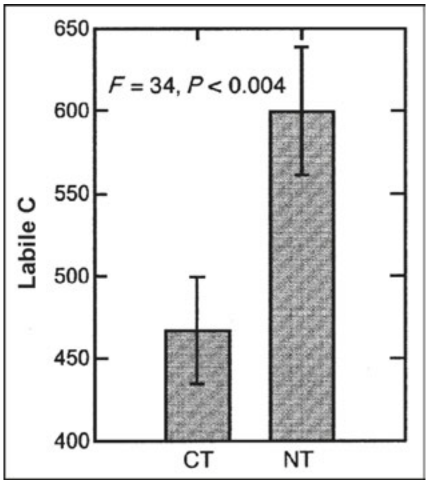

Figure 2. Effects of soil tillages on labile carbon (adapted from Weil et al., 2003). CT=conventional tillage; NT=no-till.

Measuring and Interpreting

The potassium permanganate oxidation method is currently used to measure reactive carbon. See the NRCS Active Carbon Field Test Kit (contact the Kellogg National Soil Survey Laboratory in Lincoln, Nebraska, for more information). Cornell University has developed a scoring curve (only valid for the region of New York) based on the research work of Andrews et al. (2004) to interpret soil quality indicator values for RC in the New York area. Figure 3 shows the scoring for RC (red=constraint, yellow=potential constraint, blue=no constraint).

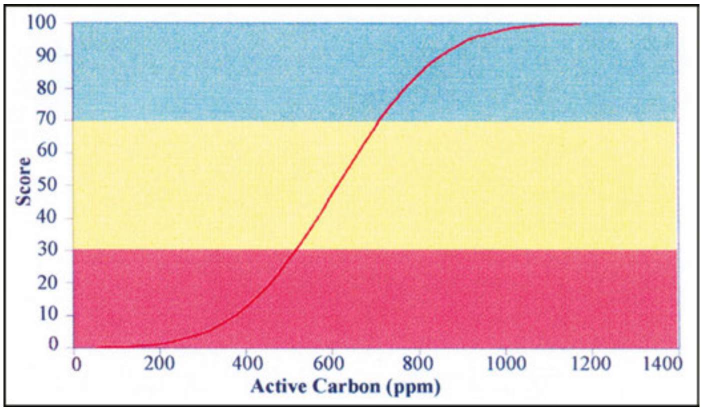

Figure 3. Reactive carbon interpretation (Cornell University Soil Health, unpublished).

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United States Department of Agriculture

NRCS

Natural Resources Conservation Service

Soil Quality National Technology Development Team

January 2009

Soil Quality: Managing Cool, Wet Soils

Issued January 2009

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Soil Quality:
Managing Cool, Wet Soils

Dealing with cool, wet soils

When dealing with cool, wet soils, the first thing is to realize that this is a complex system. Major alterations of individual properties (physical, chemical, biological) can impact the whole soil ecosystem in the absence of conservation practices.

This technical note will show that by mimicking nature through limiting physical disturbance and increasing crop diversity, one can better manage cool, wet soils.

Before beginning to optimally manage cool, wet soils, we must first understand a few basic principles that will lay the foundation for best management practices.

One major soil function is to permit water infiltration. Soil infiltration is often reduced by tillage. Tillage destroys soil aggregates. Destruction of soil aggregates negatively impacts soil porosity (air spaces in the soil). When soil porosity is reduced, infiltration (the rate water travels in the soil) is reduced and the subsequent runoff is increased; furthermore, free exchanges of gases between soil and atmosphere are hampered. Roots need a porous medium for gas exchange and water availability to achieve optimum growth. Water infiltration into cool, wet soils is important for several reasons, particularly its effects on the freeze/thaw cycle and soil structure.

This technical note will illustrate that cool, wet soils can be managed without disrupting the soil ecosystem.

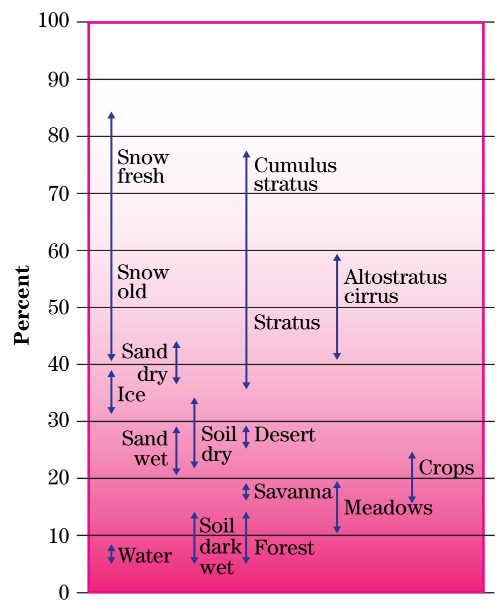
Understanding the natural system

Understanding the natural system is crucial in understanding the problems associated with cool, wet soils. Snow cover is one of the most important climatic features of cool, wet soils because of its influence on energy and moisture budgets. Snow is highly reflective. Without snow cover, the ground absorbs about four to six times more of the Sun's energy.

In areas where snow cover is disappearing earlier in the spring due to climate change, large amounts of energy that would have melted the snow can now directly warm the soil. Snow cover accounts for the large differences between summer and winter land surface albedo. The albedo of an object is the extent to which it diffusely reflects light from the Sun. Most land areas have an albedo of 10 to 40 percent. The average albedo on Earth is about 30 percent. Dark, wet soils have an albedo roughly of 6 to 15 percent, and dry soils have an albedo of 22 to 34 percent (fig. 1) (Grobe 2006). Crops have an albedo of 16 to 25 percent. Dark soils have low albedo, which means they absorb more sunlight (electromagnetic radiation) and reflect very little, thus heating up quicker than lighter colored soils. A daily life example of the albedo effect is people who wear dark clothes in the summer put themselves at greater risk of heatstroke than those who wear light-colored clothes.

Researchers and farmers both find that it takes a longer time for wet soils to warm up. The reason wet soils take longer to warm up is the high specific gravity of water, which means it takes a lot of energy to heat

Figure 1 Percentage of diffusely reflected sun light in relation to various surface conditions of the earth (Grobe 2006)



the soil water. Even though color and texture impact how quickly soils warm up, it is the soil water in cold climates that plays the largest role in the soil warming process in the early spring. This is why it is important to have good infiltration in soils.

A light-colored soil with a high albedo that is saturated with water will reflect the light, the soil will not absorb the heat from the light, and the high water content will delay the soil from warming. In other words, dark soils heat up faster than light ones. Dark color is a reasonable indicator of soil carbon. Therefore, in theory, increasing soil carbon will darken the soil's color and decrease its albedo, potentially leading to warmer spring soil temperatures. But in reality, that does not always occur. Soils with high organic matter content hold more water. More water means more energy is needed to warm the soil profile. The best way to warm the soils is to increase infiltration, and to increase infiltration, decrease tillage.

Snow cover impacts soils

The effects of snow and frost on soil water dynamics are extremely complex. Partitioning of snowmelt into soil surface infiltration and runoff is influenced by soil drainage characteristics, soil frost conditions, infiltration, soil water storage capacity, and snowmelt rates. Zhao and Gray (1999) report that numerous studies found seasonal infiltration is inversely related to the total moisture content of a soil at the time of melt.

Research has shown that soil freezing can alter the dynamics of water flow and nutrient cycling during snowmelt (Brooks and Williams 1999). Seasonal snow packs in the northern latitudes are well known to reduce soil freezing by insulating the soil surface; frost depth generally varies inversely with snow depth. Lack of snow or a late snowpack accumulation results in soil freezes that are deeper and of longer duration than when the snowpack is established in early winter (Shanley and Chalmers 1999).

A study of drainage in agricultural land indicated that high water content soils at the onset of freezing reduced infiltration of snow melt (Schimel and Kieland 1996). Freezing influences the potential for interaction between snowpack nutrients and soil microbes, which are critical regulators of nutrient cycling and retention during these periods.

Concrete frost, which is partially saturated soil that freezes so pores are filled with ice, has very low permeability that greatly reduces infiltration of snowmelt or rain and promotes overland flow. Soils in no-till systems have less concrete frost because no-till soils have larger soil pores compared with the same soil under conventional tillage. Soils in conventional-tilled systems have a smaller soil pore, which creates more concrete frost.

When soil aggregates are destroyed, pore spaces between soil aggregates are decreased. With decreased pore space, it is easier for ice to bridge the gap between the remaining aggregates, which creates an impermeable surface like concrete, thus the term "concrete frost." Concrete frost inhibits infiltration, water flow, and nutrient cycling by soil microbes (fig. 2).

Granular frost occurs when unsaturated soils freeze (fig. 3). This results in a more permeable soil, allowing more infiltration and less overland flow than concrete frost.

Figure 2 Conceptual diagram of concrete frost

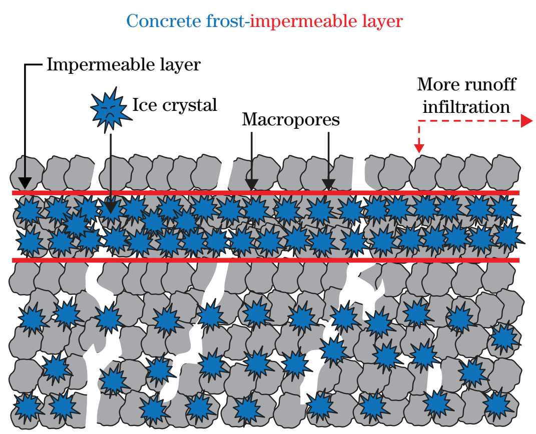
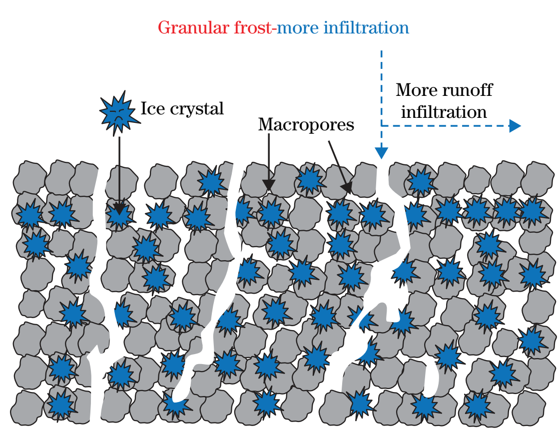


Figure 3 Conceptual diagram of granular frost



Increasing granular frost
During the winter months, soils function best in a **granular frost condition**. This occurs when permeable soils freeze under unsaturated conditions. Although the soil is frozen, infiltration still occurs and overland flow is minimized. Good soil structure with intact soil aggregates will increase infiltration rates, thus decreasing the water content in the soil. Granular frost in soils reduces the opportunity for ice to bridge the pore spaces between the aggregates, maintaining permeability.

How can the soil system be managed to increase soil function and productivity?

The better the soil is functioning (e.g., infiltrating), the fewer problems there will be with concrete frost and other associated water issues (Johnson and Lundin 1991). Functioning soils capture needed rain throughout the growing season. During the winter months, soils will infiltrate and drain water throughout the soil profile as quickly as possible, which reduces water accumulation on the surface. Figure 4 shows what happens when soil pores are reduced in size.

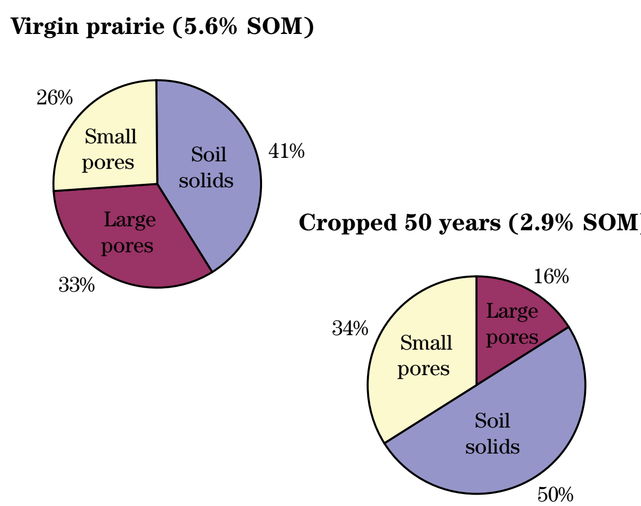
Soil quality principles that increase soil function in cool, wet soils:

- *Reduce physical and chemical soil disturbance (tillage and pesticides)*—managing a soil with tillage is like fixing a Swiss watch with a sledge hammer. Using the wrong tool can create a worse problem. Physical disturbance, like tillage, depletes organic matter, increases soil crusting which reduces infiltration, increases concrete frost by reducing average pore space, and disturbs microbial function. All these factors impact water infiltration and nutrient availability throughout the growing season. Another type of disturbance that can be harmful to the soil ecosystem is "chemical disturbance." Certain fungicides, insecticides, and herbicides can be harmful to soil fungi, bacteria, and earthworms. These living organisms are critical for increasing infiltration and nutrient cycling. Tillage in cool, wet soils can create a string of events that can cause more harm than good.

  Most wet areas in a field are wet because they receive additional water from higher places on the landscape by surface or subsurface flow and do not have an outlet for the excess water. Runoff is increased because tillage destroys the surface porosity needed for water to soak into the soil. One pathway water takes to infiltrate the soil is between soil aggregates. Tillage shears soil aggregates, leaving fewer pathways between aggregates and clogging the spaces that remain with the smaller pieces of smashed aggregates (fig. 5) (Laws and Evans 1949). Another way tillage impedes infiltration is by destroying worm and root channels. Pores that are not continuous with the soil surface do not conduct water down into the soil very well.

Figure 4 Reduced pore size caused by tillage

Figure 5 Effect of 50 years of continuous cropping on soil porosity (Adapted from Laws and Evans 1949)



The net result is more water in low areas with no place to go but up (evaporation). When the weather and soil are cool in the spring, evaporation is a slow process. The best way to warm up the soil in these conditions is to use a pinwheel placed in front of a no-till drill. The pinwheel will push away the residue from the seedling, thus allowing the soil to warm next to the seedling without disturbing the soil. In sod or pasture applications, ripple coulters throw less soil and work well in heavy soils.

- *Use cover crops*—Cover crops are a good way of solving water problems in the winter. Cold-tolerant cover crops such as winter wheat and rye, which survive through the winter, have the ability to utilize excess moisture and increase soil strength to ensure an earlier planting date. Ongoing research by Osborne and others (2002) in Brookings, South Dakota, indicates that soil bearing strength and trafficability is increased with cover crops. The study revealed that conventional-tilled fields and fields that grow no cover crops have a lower bearing strength versus no-till fields with cover crops (fig. 6). Soils with cover crops have more root and worm channels. The roots in cover crops act like stabilizers in the soil, similar to rebar in concrete. Improved bearing strength may be related to the above biomass characteristics and the root system. In general terms, the experiment illustrated the ability of cover crops to utilize excess soil moisture and increase soil strength compared to conventional tillage or no cover crop (Osborne et al. 2002).

  Some other benefits of cover crops are:

  – Cover crops increase nutrient cycling.

  – Cover crops enhance soil habitat for all types of soil microbes.

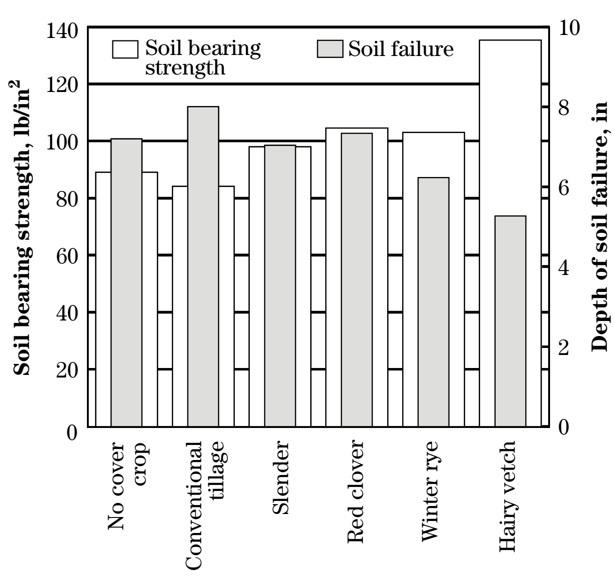
  – Cover crops improve water cycling in the soil profile.

  – Cover crops increase soil biodiversity.

- *Reduce compaction*—Nature has built-in processes that will reduce soil compaction cycles of wetting and drying and freezing and thawing. In the last 30 to 40 years, farming practices have changed drastically, creating situations where natural rejuvenation of the soil environment by wet-dry and freeze-thaw cycles is inadequate to maintain optimum conditions for crops.

  Performing field operations on wet soils, using multiple field operations for crop production, eliminating perennial crops from crop rotations, and using heavy equipment contribute to more extensive and deeper compaction.

Figure 6 Bearing strength of soil (Osborne et al. 2002)



Management strategies for eliminating compaction:

- *Stay off wet soil*—Soil is most susceptible to compaction when soil water in the 3- to 6-inch soil depth is near field capacity or wetter. Under such moisture conditions, the potential for compaction increases as soil clay content increases and soil organic matter decreases.
- *Reduce tillage*—Tilled soils are more susceptible to compaction than no-till soils. Tillage contributes to the breakdown of soil structure by compressing and breaking soil aggregates, which are necessary for good air and water movement and good root growth. Tillage also results in the loss of soil organic matter, which is important to soil aggregate stability. Using a pinwheel in front of the no-till drill will help remove the residue away from seedling allowing the soil to warm up quicker.
- *Build organic matter in soil*—Organic matter promotes the development of good soil structure and decreases soil bulk density. It helps bind soil particles together as aggregates so they are not as easily cracked, split, or compressed by tillage or wheel traffic. Reducing disturbance and increasing diversity will increase organic matter.

- *Increase diversity of rotations with perennial crops or deep rooted crops*—When crop rotations include alfalfa, clover, or grass, soils usually are less compact than soils in fields without these rotations. The deeper rooting depth of alfalfa and clovers helps keep the soil more porous and overall produce more organic matter.

Conclusion

Nature is very complex. Trying to alter the way the soil ecosystem functions is usually expensive, ineffective, and detrimental in the long run. As we mimic the natural soil ecosystem by using cover crops and minimizing chemical/physical disturbance, the effectiveness of our efforts to manage cool, wet soils is accelerated.

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Soil Quality Information Sheet

Rangeland Soil Quality—**Organic Matter**

USDA, Natural Resources Conservation Service **May 2001**

What is soil organic matter?

Soil organic matter is carbon-rich material that includes plant, animal, and microbial residue in various stages of decomposition. Live soil organisms and plant roots are part of the carbon pool in soil but are not considered soil organic matter until they die and begin to decay.

The quantity and composition of soil organic matter vary significantly among major ecosystems. Soil in arid, semiarid, and hot, humid regions commonly has less organic matter than soil in other environments. The total content of organic matter ranges from less than 0.5 to more than 8 percent in the surface layer of rangeland soils.

Soil organic matter includes three main components (table 1). The **light fraction** is more biologically active than the other two and includes relatively fresh plant fragments. **Physically protected** organic matter is locked within aggregates of mineral particles, where it is protected from microbial decomposition. **Chemically stable** organic matter gives soil its dark color and is generally the largest pool of organic matter in soil. Physically protected organic matter may also be chemically stable.

Table 1.—Soil organic matter

Component	Rate of decay	Primary function
Light fraction	Weeks to months	• Serves as food for soil organisms • Stores and provides plant nutrients
Physically protected	Decades	• Enhances soil structure, porosity, and the water-holding capacity
Chemically stable	Hundreds to thousands of years	• Holds nutrients • Stabilizes microaggregates

Why is organic matter important?

Soil organic matter enhances soil functions and environmental quality because it:

- binds soil particles together into stable aggregates, thus improving porosity, infiltration, and root penetration and reducing runoff and erosion;

Organic mattter darkens and stabilizes the surface layer in soils.

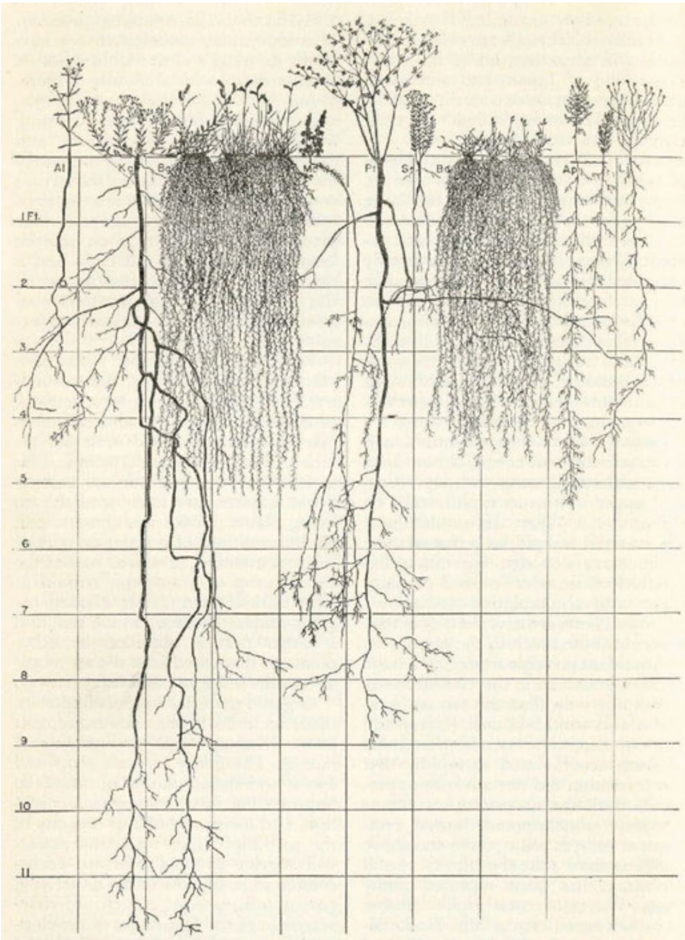
- enhances soil fertility and plant productivity by improving the ability of the soil to store and supply nutrients, water, and air;
- provides habitat and food for soil organisms;
- sequesters carbon from the atmosphere;
- reduces mineral crust formation and runoff; and
- reduces the negative water quality and environmental effects of pesticides, heavy metals, and other pollutants by actively trapping or transforming them.

What affects soil organic matter?

The amount of organic matter in the soil is a balance between additions of plant and animal materials and losses through decomposition and erosion.

Environmental factors interacting over time affect the amount of organic matter in soil. Rainfall and temperature affect plant productivity and the rate of organic matter decomposition. Increasing levels of organic matter promote a higher water-holding capacity, which results in increased plant growth and thus an increased amount of organic matter and plant nutrients.

Roots are the primary source of organic matter. Dead roots and gelatinous materials exuded by plant roots as they grow through the soil are decomposed by soil organisms and converted into organic matter. Since much of what is produced above ground is lost through photo-oxidation, the amount of



root production is very important. Every year, about 25 percent of the total root biomass in areas of tall prairie grasses dies and becomes available for incorporation into the soil as organic matter. In the drier areas, such as areas of short prairie grasses, about 50 percent of the root biomass becomes available, but the total amount is less than that in the areas of tall grasses.

Plant composition and distribution control the distribution of organic matter. The horizontal and depth distribution of roots, the distribution of plants across the landscape, and the susceptibility of roots to decay vary among species. The roots of forbs and shrubs generally contribute less organic matter to the surface layer of the soil than the roots of grasses. Changes in the composition of plant species, especially from grasses to shrubs, affect the contribution of roots to soil organic matter. The organic matter is enhanced by litter beneath shrubs in areas of arid and semiarid rangeland. Fire initially reduces the amount of plant residue added to the soil. If the fire results in a shift from shrubs to grasses, however, the long-term effect can be an increase in soil stability and organic matter.

Soil organisms break down litter, dead roots, and organic matter into smaller fragments and compounds. As they decompose organic matter, they convert nutrients into plant-available forms and release carbon dioxide into the atmosphere. Warm, moist soil supports higher decomposition rates than waterlogged, dry, or cool soil.

Wind erosion and water erosion increase losses of organic matter. Erosion breaks down soil aggregates, exposing physically protected organic matter to decomposition and loss. Organic-rich soil from the surface layer is carried away by runoff or wind. Litter redistribution by wind or water from or to surrounding rangeland also affects the content of organic matter.

Grazing can change plant composition and distribution and increase or decrease the amount of organic matter in the soil. Grazing can increase the rate of root turnover, but overgrazing reduces the amount of plant energy available for the growth of new roots. Trampling by livestock can help to incorporate the plant material above the ground into the soil. In arid ecosystems, however, little plant material is available for incorporation. Trampling also breaks up soil aggregates, exposing organic matter to decomposition and loss through erosion.

Management strategies

The following strategies can help to maintain the optimum content of organic matter in rangeland soils:

- Increase or maintain plant production.
- Promote the growth of species with high root production and promote a mix of species with different rooting depths and patterns.
- Promote the incorporation of above-ground plant material in moist plant communities with large amounts of standing plant material (e.g., areas of tall prairie grasses).
- Protect the soil from erosion by maintaining or increasing the plant cover and reducing the amount of bare soil.
- Properly manage grazing, fire, and vehicle use and thus promote the desired plant community and protect the soil from erosion.

For more information, check the following: http://soils.usda.gov/sqi **and** http://www.ftw.nrcs.usda.gov/glti

(Prepared by the Soil Quality Institute, Grazing Lands Technology Institute, and National Soil Survey Center, Natural Resources Conservation Service, USDA; the Jornada Experimental Range, Agricultural Research Service, USDA; and Bureau of Land Management, USDI)

Total Organic Carbon

Total organic carbon (TOC) is the carbon (C) stored in soil organic matter (SOM). Organic carbon (OC) enters the soil through the decomposition of plant and animal residues, root exudates, living and dead microorganisms, and soil biota. SOM is the organic fraction of soil exclusive of non-decomposed plant and animal residues. Nevertheless, most analytical methods do not distinguish between decomposed and non-decomposed residues. SOM is a heterogeneous, dynamic substance that varies in particle size, C content, decomposition rate, and turnover time.

Soil organic carbon (SOC) is the main source of energy for soil microorganisms. The ease and speed with which SOC becomes available is related to the SOM fraction in which it resides. In this respect, SOC can be partitioned into fractions based on the size and breakdown rates of the SOM in which it is contained (table 1). The first three fractions are part of the active pool of SOM. Carbon sources in this pool are relatively easy to break down.

SOM contains approximately 58% C; therefore, a factor of 1.72 can be used to convert OC to SOM. There is more inorganic C than TOC in calcareous soils. TOC is expressed as percent C per 100 g of soil.

Factors Affecting

Inherent - Soil texture, climate, and time all affect SOC accumulation. Soils rich in clay protect SOM from decomposition by stabilizing substances that bind to clay surfaces. Aggregation, enabled by the presence of clay, also protects SOM from microbial mineralization. Extractable aluminum and allophanes (present in volcanic soils) can form stable compounds with SOM that resist microbial decomposition. Warm temperatures decrease SOC content by increasing decomposition rates, while high mean annual precipitation increases accumulation by stimulating the production of plant biomass and associated SOC. With time, the breakdown of SOM produces humus-carbon, which resists decomposition by microorganisms.

Carbon loss via soil erosion results in SOC variations along the slope gradient. Level topography tends to have much more SOC than other slope classes. Both elevation and topographic gradients to some extent control local climate, vegetation distribution and soil properties, as well as associated biogeochemical processes, including SOC dynamics. Microclimate cooling with elevation may favor SOC accumulation. An analysis of factors affecting C in the conterminous United States concluded that the effects of land use, topography (elevation and slope), and mean annual precipitation on SOC are more obvious than that of mean annual temperature. However, when other variables are highly restricted, there is clearly a decline in SOC with increasing temperature.

Dynamic - Depending upon the rate of C mineralization, the amount and stage of decomposition of plant residues and organic amendments added to soil controls accrual of SOC. Turnover times for various organic materials shows that humus-carbon mineralizes slowly and thus accumulates in the soil, whereas microbial biomass C may disappear relatively quickly (table 1). Soil aggregates of different sizes and stability are possible sites for physical protection of SOM from decomposition and C

Table 1. Size and breakdown rates of various soil organic matter fractions.

Soil Organic Matter Fraction	Particle Size (mm)	Turnover Time (years)	Description
plant residues	≥ 2.0	< 5	recognizable plant shoots and roots
particulate organic matter	0.06 – 2.0	< 100	partially decomposed plant material, hyphae, seeds, etc
soil microbial biomass	variable	< 3	living pool of soil organic matter, particularly bacteria and fungi
humus	≤ 0.0053	< 100 – 5000	ultimate stage of decomposition, dominated by stable compounds

mineralization. Soil disturbance and destruction of aggregates may be the major factor responsible for increasing exposure of SOM physically protected in aggregates to biodegradation.

Crop residues incorporated in or left on the soil surface reduce erosion and SOC losses in sediment. Liming to increase the pH of acidic soil increases microbial activity, organic matter decomposition, and CO_2 release. Diversity of the soil microbial population also affects SOC. For example, while soil bacteria aggressively participate in C loss by mineralization, some fungi, such as mycorrhizae, are believed to slow the decay of SOM by aggregating it with clay and minerals. SOM and SOC are more resistant inside aggregates than in free form. Soil depth affects the distribution of SOC. Thus, plowed deep soils tend to accumulate SOC in layers beneath the disturbed top soils because of restricted mineralization rates.

Relationship to Soil Function

SOC is one of the most important constituents of the soil due to its capacity to affect plant growth as both a source of energy and a trigger for nutrient availability through mineralization. SOC fractions in the active pool, previously described, are the main source of energy and nutrients for soil microorganisms. Humus participates in aggregate stability, and nutrient and water holding capacity.

OC compounds, such as polysaccharides (sugars) bind mineral particles together into microaggregates. Glomalin, a SOM substance that may account for 20% of soil carbon, glues aggregates together and stabilizes soil structure making soil resistant to erosion, but porous enough to allow air, water and plant roots to move through the soil. Organic acids (e.g., oxalic acid), commonly released from decomposing organic residues and manures, prevents phosphorus fixation by clay minerals and improve its plant availability, especially in subtropical and tropical soils. An increase in SOM, and therefore total C, leads to greater biological diversity in the soil, thus increasing biological control of plant diseases and pests. Data also reveals that interaction between dissolved OC released from manure with pesticides may increase or decrease pesticide movement through soil into groundwater.

Problems with Poor Carbon Levels

A direct effect of poor SOC is reduced microbial biomass, activity, and nutrient mineralization due to a shortage of energy sources. In non-calcareous soils, aggregate stability, infiltration, drainage, and airflow are reduced. Scarce SOC results in less diversity in soil biota with a risk of the food chain equilibrium being disrupted, which can cause disturbance in the soil environment (e.g., plant pest and disease increase, accumulation of toxic substances).

Improving Carbon Levels

Compiled data shows that farming practices have resulted in the loss of an estimated 4.4×10^9 tons of C from soils of the United States, most of which is OC. To compensate for these losses, practices such as no-till may increase SOC (figure 1). Other practices that increase SOC include continuous application of manure and compost, and use of summer and/or winter cover crops. Burning, harvesting, or otherwise removing residues decreases SOC.

Measuring Total Organic Carbon

Presently, no methods exist to measure TOC in the field. Attempts have been made to develop color charts that match color to TOC content, but the correlation is better within soil landscapes and only for limited soils. Near infrared spectroscopy has been attempted to measure C directly in the field, but it is expensive. Numerous laboratory methods are available.

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Time needed: Laboratory methods are variable.

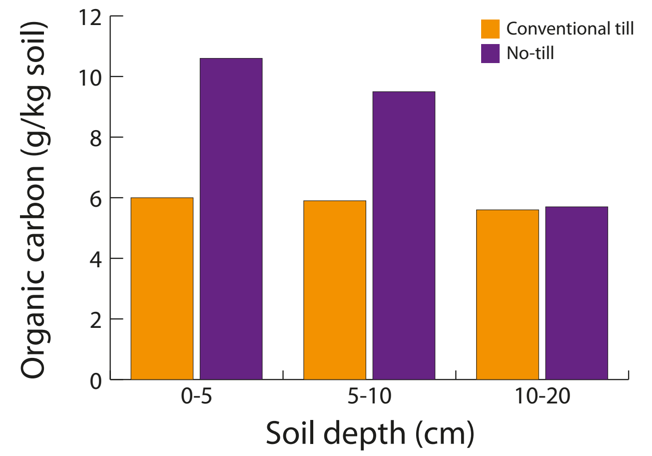

Figure 1. Effect of 10 years of conventional till and no-till on OC (calculated from SOM data in Edwards et al., 1999).

SOIL QUALITY – AGRONOMY TECHNICAL NOTE No. 12

United States Department of Agriculture

Natural Resources Conservation Service

Soil Quality Institute

Long-Term Agricultural Management Effects on Soil Carbon

Sequestration of carbon in soil has attracted attention recently because of its potential to mitigate global warming (Lal et al., 1999). However, soil carbon (C) is also valuable because of its beneficial effects on crop productivity and soil quality. Soil C is the most important soil quality indicator because of its role in other biological, chemical, and physical processes. Long-term experiments have shown the benefits of manure, adequate fertilization, and crop rotations on soil C. However, even with manure and crop rotations, conventional cropping systems generally result in a steady decline of soil C. The rate and magnitude will be affected by cropping sequence, tillage system, soils, climate, and temperature (Reeves, 1997).

Soil organic matter is about 58% carbon. Soil organic matter conversions can be made by taking soil C values in this technical note and dividing by 0.58 or multiplying by 1.72.

This technical note will examine (1) carbon dynamics in long-term cropping experiments and (2) the combined effect of conservation tillage and high biomass crop rotations on soil C. Together, these studies demonstrate the importance of reducing tillage and increasing biomass inputs.

Technical Note No. 12

August 2001

This is the twelfth note in a series of Soil Quality-Agronomy technical notes on the effects of land management on soil quality.

Series written by:

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LONG-TERM ROTATION EXPERIMENTS

Morrow Plots

Long-term rotation results are some of the best records of agricultural effects on soil C. The Morrow Plots in Illinois, established in 1876, are the oldest continuous agricultural experimental plots in the United States. Records from the Morrow experiment show consistent decrease in crop yields of monoculture corn compared to corn-oat-legume rotation. In 1944, soil C was analyzed in the plots and in the sod border surrounding the Morrow Plots (Table 1). Assuming soil C in the border was representative of the original soil C in 1876, soil C has been substantially degraded even under best management practices.

Sanborn Field

The long-term plots at Sanborn Field, Missouri (begun in 1888) show similar trends as the Morrow Plots. After 100 years of continuous cropping, soil C under continuous corn averaged 0.58% C without amendments, 1.1% C with N-P-K fertilizer applications, and 1.3% C with annual applications of 6 tons of barnyard manure/acre. Similar treatments with continuous wheat show 0.81, 1.28, and 1.6% C, respectively (Brown, 1993).

Magruder Plots

The Magruder Plots long-term continuous wheat study in Oklahoma began in 1892 (Webb et al., 1980). Soil C declined rapidly during the first 35 years and somewhat slower during the next 52 years as a steady state was approached. One of the significant lessons from the Magruder Plots is that, even with manure additions, soil C levels are not sustainable under monoculture wheat with tillage (Table 2).

Pendleton, OR

A long-term study of wheat-fallow systems was started near Pendleton, Oregon in 1931. The fields had been previously cropped since the 1880's. As yields declined, annual cropping had given way to wheat-fallow systems. The nine treatments in the study were 10 tons/acre of manure; one ton/acre of pea vine residue; 0, 40, and 80 lbs/acre of nitrogen with and without spring burning of straw; and 0 lbs N/acre with fall burning of straw. Soil C is still declining from 1931 levels in all treatments at depths down to 12 inches except the manure treatment. There is little evidence that stationary levels will be reached in the future. Although the manure treatment is not losing soil C, tillage and the fallow period are probably preventing any gains in soil C.

Table 1. Crop rotation and manure effects on soil C in the Morrow Plots, University of Illinois. Sampled in 1944 (Odell et al., 1982). Sample depth was 6 and 2/3 inches.

Crop rotation and amendment	Organic C (Tons/acre)
Eastern sod border (no treatment)	37.8
Western sod border (no treatment)	32.0
Corn-oats-clover with manure, lime and phosphorus	31.2
Continuous corn (no amendments)	16.6

Table 2. Soil C trends in monoculture wheat at the Magruder Plots, Oklahoma State University (Webb et al., 1980).

Treatment	1892 Original Soil C%	1927 Soil C%	1979 Soil C%
Unfertilized wheat	2.0	1.0	0.64
Wheat with manure applications	2.0	1.6	0.87

Can soil carbon levels be maintained with tillage?

In Iowa it was shown that if enough corn residue was produced (5,352 lbs/acre) and turned under with a moldboard plow, soil C could be maintained on a Typic Hapludoll (Larson et al., 1972). However, after years of continuous corn, the level of soil C in this study was maintained near an equilibrium of only 1.8% C (Reeves, 1997). Soil C of similar native prairie soils is approximately 4% (Robinson et al., 1996). Even in the Pendleton example, where 10 tons of manure were added annually without straw burning, tillage prevented major gains in soil C. The effect of tillage on soils in cool wet climates is less than on soils in warm wet climates.

Thus, long-term studies show that continuous tillage and row crop production reduce soil C from the levels under native vegetation. After soil C has been reduced to a lower equilibrium level, the lower C level can be maintained under conventional tillage if the amount of C returned from amendments and residues equals or exceeds that lost to decomposition.

CONSERVATION TILLAGE

The long-term experiments reviewed above compared several crop rotations and fertility treatments under conventional tillage. This section will review other long-term studies that document carbon changes under conservation tillage systems. They show that conservation tillage alone will slow the decomposition of soil C, but not stop or reverse the loss of C. To increase the level or sequester soil C, sources of C from crop residues, cover crops, and/or manures must be added.

Canada

In semi-arid Saskatchewan, on a silt loam soil, soil C increased under no-till continuous wheat but showed no gains in a wheat-fallow system (Campbell et al., 1995). There were no significant differences between tillage systems under the wheat-fallow system. However, on a related 11-year study on a clay soil (Campbell et al., 1996), cropping frequency did not affect soil C. Soil C increased under no-till to a depth of 6 inches on both the continuous wheat and the wheat-fallow system (4,465 lbs/acre over 11 years). The conventional tillage continuous wheat treatment also showed increases in soil C to a depth of 6 inches (1786 lbs/acre over 11 years). Only the conventional wheat-fallow system (using sweep cultivator and rodweeder with three cultivations during fallow) showed no increase in soil C in the clay soil. Most of the increase in soil C came during excellent growing seasons the last four years of the study. It was speculated that the soil's high clay content and good growing conditions explained the lack of soil C differences between cropping frequencies.

South Central Texas

In south-central Texas, cropping intensity increased soil C under no-tillage systems but not under conventional tillage (Franzluebbers et al., 1994). Cropping intensity was defined as the fraction-year the crop was grown:

- Continuous wheat = 0.5 year
- Wheat-soybean double crop = 0.65 year, and
- Wheat-soybean-sorghum rotation = 0.88 year

After 9 years under no-till, the soil C levels increased by 9% in the continuous wheat system, 22% in the wheat-soybean system, and 30% in the wheat-soybean-sorghum system. Soil C levels did not increase under conventional tillage, regardless of cropping intensity.

Crossville, Alabama

In Alabama on a fine sandy loam soil, a 10-year study was conducted comparing conservation tillage to conventional tillage with crop rotations of (1) continuous corn with wheat cover crop, (2) continuous soybean with wheat cover crop, and (3) corn with wheat cover crop and soybean with wheat cover crop. Beginning soil C at 0-6 inches was 0.58% (Table 3) on land that had been cropped for many years (Edwards et al., 1988)

Soil C increased from 0.58% C to 0.90% C (8,309 to 11,499 lbs/acre) in the top 4 inches in no-tillage cropping systems – a 55 % increase compared to the soil C in conventional tillage cropping systems. In this study, the key to maintaining soil C in conventional tillage systems and increasing soil C in no-till systems was the use of a cover crop. Rotations with corn in the rotation also increased soil C in humid areas with high decomposition rates.

Table 3. Soil C by depth with different tillage and crop rotations after 10 years in Crossville, AL (Edwards et al., 1992).

Crop rotation	Soil depth (inches)	Conventional till (Soil C %)	No-till (Soil C%)
Soybean w/wheat cover crop	0-2	0.57	0.93
	2-4	0.56	0.88
	4-6	0.58	0.58
	0-6	0.57	0.80
Corn w/wheat cover crop	0-2	0.62	1.20
	2-4	0.62	1.06
	4-6	0.58	0.63
	0-6	0.61	0.96
Corn w/wheat cover-soybean-wheat cover crop	0-2	0.59	1.07
	2-4	0.58	0.93
	4-6	0.52	0.51
	0-6	0.56	0.84

Pierre, South Dakota

Since 1987, research at the Dakota Lakes Research Farm at Pierre, South Dakota have shown that crop diversity and crop intensity have major impacts on soil C levels. The study compared several rotation systems. This note will focus on three of the several rotation systems. The three no-till systems are: (1) a wheat–fallow system, (2) a three year rotation (winter wheat–corn–pea), and (3) a four-year rotation (spring wheat–winter wheat–corn–sunflower). In 1994, a dry year, the three-year rotation yielded four bushels/acre of wheat better than the wheat-fallow system. The four-year rotation produced five bushels/acre of wheat more than the wheat–fallow system. In 1995, a wet year, the three- and four-year rotations respectively produced 10 and 6 bushels/acre more wheat than the wheat–fallow system (Beck et al., 1998). Another rotation with a three year break between wheat crops (winter wheat–corn–soybean–field pea) yielded 14 bushels more than the wheat–fallow system. Cool and wet seasons intensify the yield advantage of the longer rotations, especially in no-till systems. Reeves (1997) substantiated the advantages of crop rotations by reviewing several studies showing that crop diversity and rotations were more effective at enhancing productivity in no-till than conventional tillage because the rotations reduced disease in humid regions and enhanced water use efficiency in semi-arid regions.

CONCLUSION

Farmers may or may not see financial incentives to reduce greenhouse gases through C sequestration, but there will always be other benefits to improving soil C, including better productivity and soil quality. Soil C levels on continuously cropped land have dropped substantially over the past century. This decline is at least partially reversible while still keeping the land in agricultural production. Soil C levels can be increased through two types of land management practices: 1) increasing the input of organic matter by crop rotation systems, planting cover crops, applying manure, or improving annual productivity, and 2) reducing the loss of organic matter by controlling erosion and reducing tillage. Applying either of these two approaches can reduce or stop the loss of soil C associated with continuous cropping, but both approaches must (almost always) be used together to increase soil C levels. Climate is important in determining the rate of loss or gain of soil C. For example, in cool, humid climates it is not as critical to reduce tillage because cool temperatures reduce the loss of soil C and the adequate moisture allows high productivity. Conservationists should make it clear to their clients that increasing soil C is valuable and is practically feasible in agricultural situations. But to increase soil C, and not merely reduce the decline, most land managers must both reduce tillage and use crop rotations that increase annual productivity.

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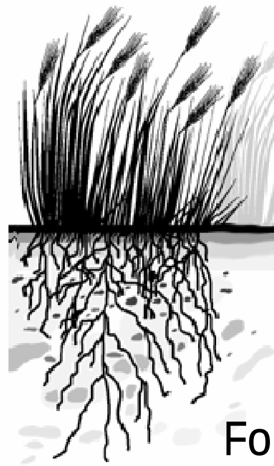

Soil Quality –
Agronomy Technical Note No. 19

Crop Residue Removal For Biomass Energy Production:
Effects on Soils and Recommendations

The promise of biomass energy

Concerns about the security and sustainability of fossil fuel use, coupled with advances in biomass conversion technology, have renewed interest in crop residue as a biofuel to partially meet our energy needs (Glassner et al., 1999). In light of the renewed interest in domestic production of biofuels and other biomass energy, can a portion of the more than 500 million tons of crop residue produced each year be used to meet some of our energy needs? The answer is not straightforward since crop residues perform many positive functions for agricultural soils that reduce erosion and promote sustainable production.

For commercial scale biofuel production, corn is receiving the most attention due to its concentrated area of production and because it produces 1.7 times more residue than other leading cereals based on current production levels (Wilhelm et al., 2004). Other high residue crops, such as rice and sugarcane, might contribute to biofuel production as a solution to residue disposal issues associated with their production (DiPardo, 2000; Wilhelm et al., 2004). Low residue crops, such as soybean, rarely produce enough residue to maintain adequate soil cover through the winter, and so are not receiving serious consideration as biofuel feedstocks.

Relatively low-cost harvest and abundance of crop residues make them competitive as gasoline additives (DiPardo, 2000). Since the rising cost of fossil fuel and related products increases the cost of agricultural production, most agree that one-pass harvest for grain and residue must become a reality to make residue-based biofuel production economically and energetically feasible (DOE, 2003). Once technology to produce ethanol from cellulosic materials is in place, it may be more efficient and the resultant fuel may have lower emissions than grain ethanol (Table 1).

Technical Note No. 19

August 2006

This is the nineteenth in a series of technical notes about the effects of land management on soil quality.

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Table 1. Comparison of Corn Grain Ethanol and Corn Stover Ethanol

Ethanol Feedstock	Net Energy Balance* (e_{EtOH} - $e_{production}$)	Percent reduction in GHG emissions/vehicle mile** E10	E85
Corn grain	25,000 Btu/gal	2%	25%
Corn stover	60,000 Btu/gal	9%	79%

*Net Energy Balance is estimated as the energy contained in 1 gallon of ethanol minus the energy required to produce it.
**Estimates of greenhouse gas (GHG) emissions from E10 (90:10 gasoline:ethanol) and E85 (15:85 gasoline:ethanol) as compared with conventional gasoline (Wang et al., 1999).

Benefits of crop residues (and the detrimental effects of removing them)

As a physical buffer, crop residues protect soil from the direct impacts of rain, wind and sunlight leading to improved soil structure, reduced soil temperature and evaporation, increased infiltration, and reduced runoff and erosion. While some studies suggest that plant roots contribute more carbon to soil than surface residues (Gale and Cambardella, 2000), crop residue contributes to soil organic matter and nutrient increases, water retention, and microbial and macroinvertebrate activity. These effects typically lead to improved plant growth and increased soil productivity and crop yield. The basic relationships between these effects are shown in Table 2.

Crop residue is managed using conservation tillage systems, such as no-till, strip till, ridge till, mulch till, and other reduced tillage methods (see NRCS Conservation Practice Standards 329, 344, 345, and 346). Most studies involving the effects of crop residues have compared no-till systems with residues to conventional tillage without residues, a presumed best case – worst case comparison, overlooking the interaction effects between tillage and residues. Karlen et al. (1994) found that 10 years of residue removal under no-till continuous corn in Wisconsin resulted in deleterious changes in many biological indicators of soil quality, including lower soil carbon, microbial activity, fungal biomass and earthworm populations compared with normal or double rates of residue return. Lindstrom (1986) found increased runoff and soil loss with decreasing residue remaining on the soil surface under no-till, with the study results suggesting a 30% removal rate would not significantly increase soil loss in the systems modeled. Reduction in these properties and populations suggests loss of soil function, particularly reduced nutrient cycling, physical stability, and biodiversity.

Table 2. General Benefits of Crop Residues to Soil Quality (after Larson, 1979)

Primary Effect		Secondary Effect		Tertiary Effect
Contributes to soil organic matter	⇨	Improves Chemical, Physical & Biological Properties	⇨	Increases yield and yield sustainability
Provides Physical buffer	⇨	Reduces raindrop impact and wind shear	⇨	Reduces soil erosion

Despite the many important benefits of crop residues, research shows some of their effects can vary. For example, some reports showed lower yields in systems with high crop residues due to increased disease or lower germination (e.g. Linden et al., 2000). Dam et al. (2005) reported poorer emergence under no-till corn with residues intact compared with residues removed and conventional till with and without residues, which they attributed to cooler soil temperatures and higher soil moisture associated with climatic conditions. Power et al. (1986) found increased crop yields for corn and soybean when residues were left on the soil surface compared with yields under residue removal in Nebraska. This yield effect was most pronounced in drier years, leading them to attribute yield increases to residue-induced water conservation.

Rate of residue decomposition varies by climate and crop, leading to varying amounts of erosion protection and organic matter additions to the soil. Due to these and other site-specific effects of residue on soil function, residue removal recommendations need to consider soil type, climate, cropping system, and management in order to protect soil quality while allowing for residue harvest for biofuel production.

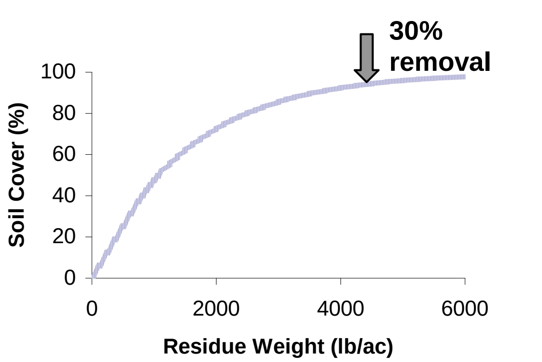

Figure 1. The relationship between percent of soil covered by residues after harvest and residue weight per acre for common small grains and annual legumes in the non-irrigated U.S. Northwest

For a more comprehensive review of the literature, see Andrews (2006).

Research considerations

Most studies examine residue removal based on weight of tissues removed at harvest, while management practices and conservation programs often concentrate on the percentage of soil covered by residue after planting the next crop. While they are related, ***a 30% residue removal rate is not the same as 70% soil cover, regardless of when soil cover is measured.*** Research by McCool et al. (1995) shows this relationship for small grains and annual legumes in the non-irrigated U.S. Northwest (Figure 1). In this example, a 30% (or 1800 lb/ac) removal rate results in 93% soil cover after residue harvest. The relationship between residue removal weight and resulting soil cover needs to be determined for that crop, if using published research recommendations to determine appropriate removal rates.

Many studies to predict residue removal effects on erosion have used the Universal Soil Loss Equation (USLE) or the Revised Universal Soil Loss Equation (RUSLE), with some assuming erosion to Soil Loss Tolerance ("T") to be sustainable. Using RUSLE2 and the Soil Conditioning Index (SCI) is probably the most expedient method to estimate sustainable residue removal rates in the NRCS field office.

Nelson (2002) estimated the amount of corn and wheat straw residue available for harvest from all land capability class I-IV soils in 37 Eastern and Midwestern states by county. To accomplish this, the crop yield (with resulting residue production) required at the time of harvest to insure that T is not exceeded was estimated for each county utilizing RUSLE or the Wind Erosion Equation (WEQ), depending on whether water erosion or wind erosion posed the greatest risk of soil loss, using NRCS databases. RUSLE or WEQ was run using measured yield averages for each county to obtain estimates of actual residue production for a three-year period.

Nelson (2002) reasoned that subtracting the predicted amount of residue required to stay at or below T (calculated from the first set of analyses) from the amount of residue calculated from actual yield data would result in the amount of residue available for harvest. Some future hurdles to predict residue harvest potential from cropping systems include extending these results to all regions and soils, other crops, and extending the prediction to include more than just soil loss as a resource concern. To fully consider the soil quality impacts of residue removal, this method should also consider effects on soil organic matter, nutrients, biota, and future crop yield.

Recommendations

To be sustainable, residue must only be removed when soil quality will not suffer as a result. In some regions the combination of crop, management practice, soil, and climate work together to produce more than is needed to maintain soil health. In this case, excess residues could potentially be used for conversion to biomass energy. However, for many other cropping, soil, and climate combinations (especially in warm regions), residue production is inadequate even for basic soil protection (Parr and Papendick, 1978). It is important to discern in what systems residue harvest is possible, or even beneficial, and at what rates (Table 3).

Table 3. General Guidelines for Sustainable Residue Harvest (after USDA-NRCS, 2006)

Sustainable harvest amounts will vary by:	Residue harvest rates should DECREASE with:	Recommendations for sustainable residue harvest:
Management practice	Increased soil disturbance	Use no-till with cover crops
Crop & yield	Lower yield or lower C:N	Harvest high residue crops and only in good yield years
Climate	Warmer, wetter climate	Residue harvest in the US SE is high-risk
Soil type	Coarser soil texture	Heavy clay, poorly drained soils are good candidates
Topography	Greater slope	Use a variable rate harvester or stay off hillsides and eroded knolls

Determine Sustainable Residue Removal Rates – Sustainable removal rates will vary by region and management system, sometimes even with fields. Removal rates will need to be reduced as climates become warmer or more humid; for lower C:N residue; for lower yielding crops; as soil disturbance (e.g. tillage) increases; and as soils become coarser textured compared to the conditions in which most studies occurred (in the Midwest Corn Belt for no-till corn).

Tools like RUSLE2, WEQ, and the SCI are likely to be the most practical ways to predict safe removal rates to maintain erosion protection and soil quality. Similar to Nelson's calculations to estimate residue harvest potential from corn and wheat systems in the East and Midwest, conservation planners in the NRCS Field Office can use RUSLE2 to determine harvestable crop residue using expected yield (and associated residue production) from producer records or county averages. Trial or 'what if' runs can be made with reduced amounts of residue (simulating harvest), to determine what amount is required to hold soil loss to T and maintain a positive SCI. The weight of crop residue available for harvest would then be determined by difference.

Use Additional Conservation Practices – Other conservation practices such as contour cropping or conservation tillage must be used to compensate for the loss of erosion protection and soil organic matter seen with residue removal (Larson, 1979; Lindstrom et al., 1981). In many regions, cover crops are a viable alternative that offer soil protection and added organic matter. Green biomass, as with a cover crop, is considered to be 2.5 times more effective than crop residue in reducing wind erosion (in predictive models), especially if the residue is laying flat (McMaster and Wilhelm, 1997).

Consider Crop Alternatives – Where crop residues are required to maintain sustainable production, a more viable option may be crops grown specifically as energy crops, including herbaceous energy crops like switchgrass and short-rotation woody crops like hybrid poplar (USDA-NRCS, 2006). Being perennials, these crops require few field passes and little soil disturbance, resulting in low erosion rates. Paine et al. (1996) recommended growing these crops on marginal lands, such as highly erodible land (HEL), poorly drained soils or areas used for wastewater reclamation, which would avoid competition with food crops and increase the amount of arable land. A large amount of land in the Corn Belt is classified as HEL (Wilhelm et al., 2004) (Figure 2), presumably making this land unsuitable for residue removal but potentially viable for perennial energy crop production.

Perform Periodic Monitoring and Assessment – Regardless of the specific residue removal practice chosen, crop fields should be carefully monitored for visual signs of erosion or crusting. Periodic checks of soil organic carbon as part of soil fertility testing are also recommended. Removal rates should be adjusted in response to adverse changes: if erosion increases or soil organic carbon decreases, removal rates must be reduced to maintain soil quality.

Summary

Because of the important function of crop residues in erosion protection and overall soil quality, their sustainable use will only be accomplished through the use of site-specific harvest rates. Using approved erosion prediction tools can help determine acceptable harvest rates. New technologies for one-pass grain and residue harvest should include within-field variable harvesting rates so that removal guidelines can be applied. Additional conservation practices to control erosion and add soil organic matter will help alleviate negative effects of residue harvest. In the long term, dedicated energy crops, such as switchgrass or woody biomass, are likely to be the most viable option. Periodic monitoring and assessment of harvested fields, coupled with the above practices, will ensure that soil quality is not sacrificed in the name of renewable biomass energy.

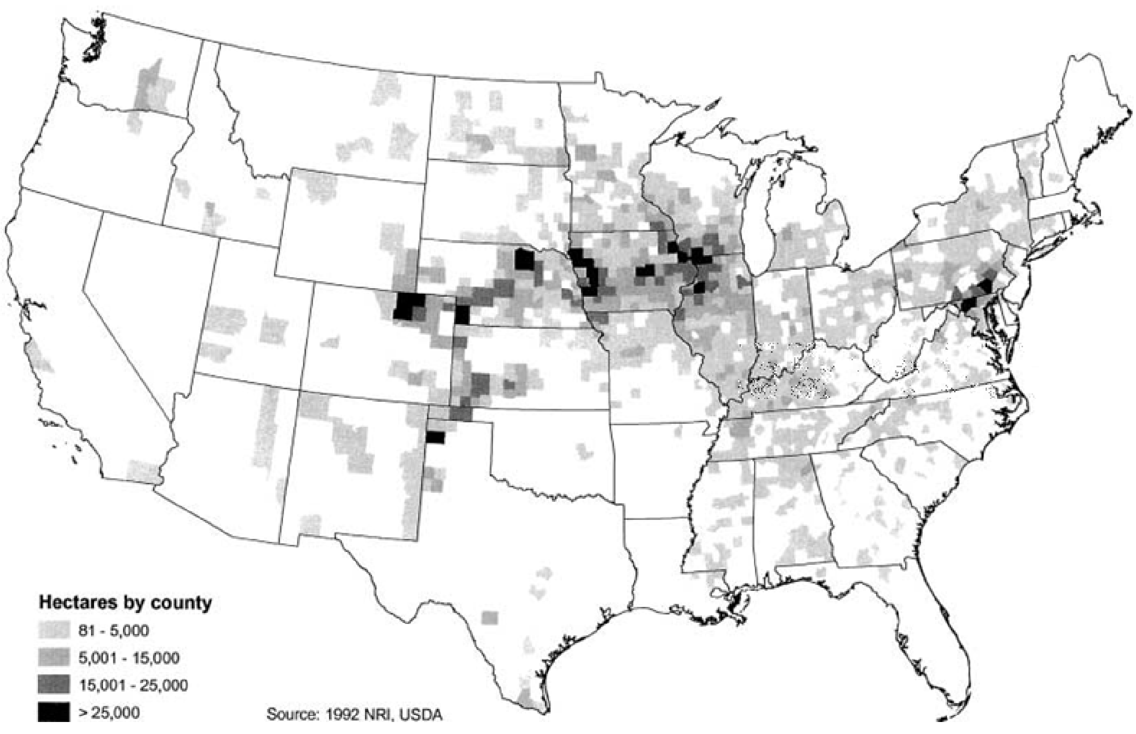

Figure 2. US Highly Erodible Cropland (USDA, 1995)

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Soil Quality - Agronomy

Technical Note No. 2

Conservation Crop Rotation Effects on Soil Quality

Conservation practices such as Conservation Crop Rotation help maintain the sustainability and the efficiency of cropland over long periods of time. Conservation Crop Rotation is a systematic sequence of crops grown in combination with other crops or with grasses and legumes. There are fewer problems with weeds, insects, parasitic nematodes, diseases caused by bacteria, fungi, and viruses when using rotations compared to monocultures. When legumes are part of the rotation, nitrogen is supplied to the succeeding crop. With forage rotations, soil organic matter will increase as a result of longer rotations. Rotations can be simple, corn followed by soybeans, or very complex, tobacco with a cover crop for two years followed by corn - double cropped wheat and soybeans using conservation tillage. Crop yields in rotation are often higher than those grown in monoculture. Practices such as conservation tillage in combination with rotations will benefit soil quality by maintaining or increasing soil organic matter. Research has shown the use of the moldboard plow reduced organic matter by an average of 256 lb/ac/yr (Reicosky, et al 1995).

Tips on Conservation Crop Rotation

- Climate and economics determine the choice of crops in rotations as well as the specific farming systems. The following principles (Magdoff, 1992) should be considered when thinking about a rotation.
- Follow a legume crop by a crop that demands high amounts of nitrogen.
- Grow less nitrogen demanding crops (small grains) the second year after a legume crop.
- Do not grow the same crop in consecutive years in order to decrease insects, weeds, diseases, and nematodes.
- Follow a crop with one that is not closely related species because of insects, diseases, weeds, and nematodes.
- Where applicable use grass or legume sod in rotations or as permanent stands on sloping highly erosive soils.
- Deeply rooted crops such as alfalfa, safflower, or sunflower penetrate to depths of 5 to 6 feet and utilize nutrients and water, and leave channels from decayed roots that improve infiltration.
- To maintain organic matter, rotate high residue crops with low residue crops or use cover crops.

Erosion

Vegetative cover has a major effect on erosion. Research shows that fourth year corn, conventionally tilled at high fertility level, had erosion rates 125 times that of highly productive grass-legume sod. Cropping systems with a higher frequency of sod will reduce erosion. Growing cover crops with low residue crops and rotation of high residue crops with low residue crops are also effective erosion control practices. Some crop rotations will not reduce erosion unless other practices such as cover crops and residue management are used. Crop rotations that utilize the land more intensively such as corn, wheat and soybeans grown in two years produce larger amounts of biomass during the rotation and are more effective in reducing erosion than a continuous cropping sequence (Heath et al 1976).

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Technical Note No. 2

August, 1996

This is the second technical note in a series of technical notes on the effects on soil quality. This technical note is general and covers broad application. For specific cropping rotations contact your NRCS State Agronomist.

Deposition of Sediment

Increase cover from grass and or legume rotations or high residue crops combined with other conservation practices such as conservation tillage will reduce upland erosion which in turn, reduces sediment from surface runoff and wind.

Compaction

Monoculture agriculture and tillage weaken soil structural characteristics increasing susceptibility to compaction (Schnitzer 1991). Sod base rotations with deep root systems can reduce compaction through the addition of organic matter and development of channels from decayed roots; thus improving water movement and aeration. Rotations that increase organic matter, microbial activity and aggregation of soil particles, will also increase porosity and lower bulk density.

Soil Aggregation at the Surface

Rotations that promote the increase of organic matter and microbial activity will increase aggregate stability. Caution: If residue is incorporated, with tillage, benefits of increased biomass is lessened.

Infiltration

Conservation crop rotation systems that promote an increase in organic matter and an increase of aggregate stability will maintain or improve the presence of pores for infiltration (Schnitzer, 1991). Decaying roots, especially those of deep rooted crops like alfalfa and safflower, will leave channels for improved infiltration. Other conservation practices may be needed in crop rotations such as crop residue management to ensure surface protection and improve infiltration. Caution: Macropores can result in an increase of leaching of highly soluble pesticides if a heavy rain occurs within a few hours after application.

Soil Crusting

If residues are left on the soil surface and sod based rotations are included with high residue crops, the increase in organic matter, improved infiltration, and increased aggregate stability will reduce soil crusting. Caution: Monoculture and low residue cropping systems with tillage will increase the decay of organic matter and reduce aggregate stability which often results in soil crusting .

Nutrient Loss or Imbalance

One of the principles of crop rotation is to precede a nitrogen demanding crop with a legume crop to provide nitrogen. Sod rotations with deeply rooted crops can penetrate to depths of 5 to 6 feet and cycle nutrients especially the more soluble nutrients such as nitrates. Crop rotations that promote increased biomass provide a slow release of nutrients to the root zone.

Pesticide Carryover

Where different crops are grown each year and crop rotations reduce the chance of pesticide buildup. The threat of pest tolerance to insecticides and herbicides are reduced with rotations (Reeves, 1994). Rotations increasing organic matter improve the environment for biological activity that will increase the breakdown of pesticides.

Soil Organic Matter

The amount and type of organic matter is indicative of soil productivity (Mitchell et al 1996). The types of crops grown, the amounts of roots, biomass yield, and efficiency of harvest, and the management of residues affect soil organic matter (Magdoff, 1993). High residue crops in rotation with cover crops and conservation tillage increase amounts of organic matter compared to conventional tillage and monoculture. ìIt is practically impossible to increase organic matter where moldboard plowing is taking placeî (Reicosky et al, 1995). Vegetables and other low residue crop rotations will need other practices such as, cover crops to increase biomass yield.

Biological Activity

There is a direct relationship to the amount of residue and the population of soil microorganisms. Research in Oregon showed wheat-fallow systems had only 25% of the microorganisms found under pasture. When rotations are more complex and include sod crops soil biological diversity will increase (Magdoff, 1993). Soil organisms that are active in the soil, include bacteria, fungi, actinomycetes, protozoa, yeast, algae, earthworms and insects. Numbers of soil

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organisms in general are proportional to organic matter concentrations in the upper 15 inches (Schnitzer, 1991). Moldboard plow tillage systems decrease earthworms and other soil organisms.

Weeds, Insects and Pathogens

Certain harmful insects and diseases over winter in the soil. Monoculture promotes increases in insects and diseases. Different crops grown in a 2 to 3 year rotation will reduce the chances for survival of insects and diseases (Agronomy Department, Virginia Polytechnic Institute, 1959). Rotations break the life cycles of specific weeds which adapted to narrow ecological niches associated with continuous cropping. Selective pressures on weeds, including crop competition, pathogens and pests, herbicide tolerance, fertility factors, and tillage are reduced when crop rotation is not practiced. (Reeves, 1994).

Soil Salinity

Conservation practices along with rotations that help control soil salinity include reducing summer fallow, increasing organic matter, use deeply rooted perennial forage crops, conservation tillage, and plant salt tolerant crops (Eilers et al 1995).

Effective crop rotations are important for sustaining productivity and conserving our natural resources. In addition to erosion protection, crop rotations increase soil organic matter and improve physical properties. They also break disease, insect and weed life cycles and improve nutrient and water usage. Conservation tillage enhances the effects of conservation rotation systems conventional tillage can often mask some of the benefits. For more information read the following references.

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SOIL QUALITY- AGRONOMY
Technical Note No.3

Effects of Residue Management and No-Till on Soil Quality

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This is the third note in a series of Soil Quality-Agronomy technical notes on the effects of land management on soil quality. This information is general and covers broad application.

Compared to water or air quality, soil quality is a relatively new concept and relies on indicators, like organic matter, bulk density, nutrient status, and microbial biomass for measuring. Of this, organic matter is probably the most vital in maintaining a quality soil resource. It improves aggregate stability and soil structure, reduces erosion potential, provides energy for microorganisms, is important to nutrient cycling, and improves infiltration, water holding capacity, cation exchange capacity, and the breakdown of pesticides. The best ways to manage organic matter in a cropping sequence are to reduce tillage, plant cover crops, and practice crop rotations to increase organic inputs as root biomass. This technical note focuses on tillage and residue management, as the practices that most influence organic matter levels. Residue management includes no-till that is the method of preparing a narrow slit or strip for a seedbed and leaving surrounding residue cover on the surface undisturbed. Other forms of residue management are mulch till, ridge till and seasonal residue management. Conventional tillage usually includes a moldboard, disk or chisel plowing, and secondary tillage that disturbs the soil surface for seed preparation. This note focuses on the least disruptive form of conservation tillage, no-till. Local soil and climate conditions may dictate other forms of conservation tillage to be used to maintain economic sustainability.

Factors Influencing Organic Matter Levels

The amount of organic matter in soil is the result of the combined influences of climate, inherent soil characteristics, land cover and use, and management practices. When rainfall or irrigation is sufficient, the amount of vegetation (biomass) increases with warmer temperatures, but rates of decomposition of the biomass also increases dramatically. Generally, organic matter increases with higher rainfall and cooler temperatures. Conversely, soil formed under warm, arid climates is usually low in organic matter mostly due to low amounts of biomass production. Soil texture is another influence on organic matter. Clayey soils generally have higher levels of organic matter than sandier soils. Soils with drainage limitations due to landscape position or a slowly permeable layer will generally accumulate more organic matter as a result of slower decomposition from the anaerobic conditions that limit microbial activity, than more freely drained, aerobic soils. Humans influence organic matter through the selection of management practices. Agronomic inputs like adding manure or fertilizers increase vegetative growth (above and below ground), thus increases soil organic matter. Crop diversity, cover and green manure crops, reduced tillage, and rotations with pasture or hay will promote accumulation of surface residue and will generally increase soil organic matter in the surface layer. Conversely, management systems that require intensive tillage and low residue crops result in greater losses of soil organic matter. In the 1850s, the moldboard plow became the standard for primary tillage. The plow turned the soil over and buried most of the residue of the native vegetation or the previous crop residue. The stirring and turning of soil stimulated microbial activity and increased the rates of residual organic matter break down. For example, the Morrow research plots in Urbana, Illinois, established in 1876, had a 23% decline in organic carbon due to tillage (Odell et al., 1982). Soil aggregates and large pores are disrupted when left unprotected from the impact of raindrops. This reduces water infiltration and increases runoff and erosion. In more arid climates, the unprotected soil surface becomes smooth, making it vulnerable to wind erosion until crusting occurs. Unfortunately, all forms of tillage decrease organic matter to some extent. Therefore, it is difficult to maintain soil organic matter levels when tillage is practiced. Adding organic materials, such as manure, may help maintain or increase the level of organic matter. However, research at Pendleton, Oregon showed that even after 40 years of adding manure at rates over 10 tons per acre per year, residual organic matter levels had not increased mainly due to tillage and summer fallow practices (Rasmussen et al., 1989). Reicosky and Lindstrom (1993) measured carbon dioxide released from soil 19 days after wheat stubble had been plowed. The moldboard plow caused as much carbon to be oxidized as had been photosynthesized in the roots and residue during the whole growing season. This rate was 5 times greater than the untilled plots. In summary, research has shown that it is practically impossible to increase organic matter when the entire land surface is tilled.

Tillage Effects on Organic Matter

Adoption of no-till has increased in acreage from approximately 14 million acres to nearly 41 million acres from 1989 through 1995 (Conservation Technology Information Center, 1996). Some of the benefits of no-till are erosion control, fuel, labor and time savings. Researchers have shown that no-till increases soil organic matter in the surface three inches (Ishmal et al., 1994; Mahboubei et al., 1993). However, the residue cover from no-till protects the soil surface from erosion and preserves the continuity of water conducting pores. The best way to increase organic matter throughout the surface is through the use of cover crops or sod rotations in conjunction with no-till (See Technical notes No. 1 and No. 2). Reicosky et al., (1995), summarized 9 long term no-till studies, all of which showed that organic matter increased an average of 986 pounds per acre per year, or about 0.1 percent per year. Locations of these studies were in the states of Minnesota, Nebraska, Illinois, Ohio, Kentucky, Georgia, and Alabama. Research ranged from 5 to 11 years, and rates of increase ranged from 80 pounds to 2,000 pounds of average annual residual soil organic matter. These increases were the result of no-till, crop rotations with grain crops and cover crops. Increases would not be expected in low residue crops without rotations of grain crops and the addition of cover crops. Increases in organic matter affect properties such as cation exchange capacity, aggregate stability, and available water holding capacity.

Impacts on Aggregate Stability/Soil Structure

Residues, left on the surface, increase aggregate stability. Soil aggregates, in no-till systems, are more stable than in conventional tillage soils due to the added strength provided by products from the decomposition of soil organic matter and presence of bacteria and fungal hyphae. The hyphal material acts like strings that bind or tie smaller aggregates and soil particles together. A demonstration was recently conducted in the Central Valley of California compared cover crops in an orchard tilled annually, to permanent cover crops. To illustrate the benefits of a permanent cover, the researchers placed one clump of soil in a glass of water from the untilled site that had accumulated surface organic matter, and one from the tilled site that had not. The tilled sample began to disperse immediately and the water became very cloudy. The untilled sample with increased surface organic matter was stable and the water remained clear. Surface residues in no-till systems help protect aggregate stability and maintain the continuity of soil pores resulting in increased infiltration rates and reduced soil erosion.

Impacts on Biological Activity

It is generally acknowledged that residues have several positive effects on the microbial populations in agricultural systems. Residue accumulations in the surface 3 inches provide cooler and moister environments than conventional tillage systems. Surface residues provide more substrates or food for nitrifying and denitrifying microbes. The increased residues, with high carbon to nitrogen ratio, slow the rate of mineralization over a longer period of time (Coleman and Crossley, 1996). Soil invertebrate populations such as microarthropods and earthworms increase with less tillage as a result of increased populations of litter-decomposing fungi and help's increase nitrogen availability for plant growth. Research comparing 22 components of no-till and conventional tillage (House, et al. 1984), indicated no-till systems had greater resilience, greater invertebrate species richness, greater soil organic matter, and nitrogen turnover time. The following table highlights some of the components compared between no-till and conventional tillage.

Component	No-Till vs. Conventional
Crop Yields	NT=CT (except during drought)
Weed Biomass	NT>CT
Residue Decomposition Rates	CT>NT
Surface Crop & Weed Residues	NT>CT
Surface Litter (%N)	NT>CT
Nitrification Activity	NT>CT in upper soil layer
Total Soil N	NT>CT in upper soil layer
Organic Matter	NT>CT
Soil Moisture	NT>CT
Foliage Arthropods	CT=NT
Arthropods Species Diversity	NT>CT

High residual organic matter levels increase the general fertility and productive capacity of soil (Moldenhauer et al., 1995). Residual organic matter and slow decomposition rates provide crops with a limited but continuing source of nutrients. Residual organic matter also promotes deeper rooting by improving infiltration and water holding capacity.

Management Concerns

Soil compaction may become a problem with no-till. Limited deep tillage and strip tillage may be useful in breaking up compacted areas without disrupting the entire surface area. Also, no-till crop production in the beginning, may require more chemical weed control, but over time the residue cover increases to the point weed seeds cannot germinate because they are not brought to the surface by tillage. Vines and other perennial weeds can become more prevalent in no-till monoculture systems, because certain weeds may not be controlled by the herbicides. Crop rotations with no-till systems may alleviate some pest and compaction problems. In agricultural soils that have been degraded, it may take 3 to 5 years to see benefits from no-till. However, no-till used in combination with crop rotations and cover crops can be a valuable tool for improving the soil resource.

Summary

Organic matter is one of the most important indicators of soil quality. Some of the beneficial effects of soil organic matter include better aggregation and aggregate stability, longer cycling of nutrients, higher microbial activity, more water holding capacity, greater cation exchange capacity, and lower bulk density. Tillage operations have a significant effect on soil organic matter. Even high inputs of manures have limited success in maintaining levels of soil organic matter if the soil is continually tilled. Following are some beneficial practices for protecting soil organic matter.

1. No-till and other reduced tillage practices leave residues on the surface and protect the soil from wind and water erosion.

Along with crop residue the no-till system increases aggregate stability, organic matter, microbial activity and invertebrates, infiltration, and available water holding capacity.

2. Crop rotations provide biodiversity to reduce insects, weeds, and disease in no-till systems.

3. Cover crops provide protection of the soil surface, add residue, and organic matter to the soil.

4. Rotations that include grass and legumes are good for erosion control and increase organic matter.

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USDA United States Department of Agriculture

NRCS Natural Resources Conservation Service

Soil Quality Institute

Sod-Based Rotations:
A Proven Old Practice to Improve Soil Productivity

Technical Note No. 18

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This is the eighteenth in a series of technical notes about the effects of land management on soil quality.

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Historical overview

Sod-based rotations are those that alternate sod-forming grasses and legumes with row crops and cereal grains. The grass and/or legumes should break up the row crop cycle for more than 1 year.

Farmers in many countries, including France and England, have learned over centuries that grass-based systems are essential for maintaining the long-term productivity of soils (Albrecht, 1938). The most important benefits of sod relate to the accumulation of organic matter facilitated by the extensive root systems of perennial grasses. In fact, the productivity of sod-based virgin soils is typically associated with high levels of organic matter. As American settlers spread west, they cleared trees and sod and cultivated the land. The result of this clearing and plowing was the loss of one of our most valuable resources—soil organic matter.

Many long-term studies in the United States have documented trends of organic matter losses on agricultural land (NRCS Soil Quality Institute, 2001). Cultivated cropland typically has only 50% of the organic matter of soils that support native vegetation. These same studies show significant advantages of grass-based systems over continuous cropping for maintaining or increasing the content of organic matter. For example, the Morrow plots in Illinois and the MacGruder plots in Oklahoma showed that fertility, productivity, and organic matter content all declined under continuous cropping systems and then leveled off after approximately 75 years. The organic matter levels of these soils began around 4% and steadily degraded to 1–1.5% under the corn-soybean-wheat rotation. In contrast, the highest organic matter levels were under the long-term rotations with grass (Wright et al., 2002).

Unfortunately, when cultivated crops are grown in rotation with grass, organic matter levels rapidly decline and rise again only when the land is returned to sod. Thus, it is critical to use conservation tillage during the cropping phase of a sod-based rotation to preserve the benefits of grasses and legumes.

History has shown that the benefits of sod-based rotations may be greatest on soils that have limitations because of erosion hazards, drought stress, or restricted soil depth. In the past, many of these marginal lands were farmed as mixed crop-livestock enterprises. As agriculture became more specialized after World War II, sod became less common on farms. Soil degradation (from loss of organic matter and erosion) coupled with higher costs of inputs forced many farmers to quit farming and to plant trees or a permanent grass cover. These same conditions–soil degradation and high input costs–have created a renewed interest in including sod-based rotations and cattle grazing along with crop production on a variety of lands.

Benefits of sod-based rotations

Sod-based rotations provide several benefits to commercial agriculture. Perhaps the greatest benefit is improved yields as a result of enhanced soil quality (Reeves, 1997). The fibrous roots from grasses and the taproot systems of legumes help to build organic matter levels and improve soil structure. Including sod in the crop rotations increases diversity and breaks pest cycles, thus reducing pressure from insects, root-feeding nematodes, weeds, and diseases. Adding legumes to sod rotations supplies nitrogen to the soil, reducing the amount that must be applied for the accompanying grasses.

Many farmers agree that crops grown after years of grass sod generate 50–100% higher yields than continuous crops. For example, the average peanut yield in the Southeast U.S. is about 2,500 lbs per acre, but yields after bahiagrass (*Paspalum notatum* L.) are often 3,500–4,500 lbs per acre. Economic modeling showed that profits for cotton and peanuts in a sod-based rotation were about two times greater than those for a peanut-cotton-cotton rotation (Marois et al., 2002). Yield increases can be attributed to soil quality improvements following perennial sod, including increased soil organic matter and water-holding capacity, better soil structure and water infiltration, and decreased erosion compared to continuous cropping or even following green manure cover crops (Wright et al., 2002). Cooper and Morris (1973) referred to soil organic matter and associated improvements in soil properties when they stated that the sod in a wheat-sod rotation put the *heart* back into the soil.

Deep-rooted sods can increase the potential rooting depth for subsequent crops (Marois et al., 2002). Elkins et al. (1977) showed the importance of grass rotations for increasing rooting depths on the Southeast Coastal Plain. They calculated that, given an evaporation rate of 0.17 inches of water per day and available water of 1 inch per foot of soil, plants with a 6-inch rooting depth would experience water stress in 3 days without rainfall or irrigation. Plants with a 5-foot rooting depth would not experience water stress until 30 days after rainfall.

Since 1962, researchers in Uruguay have studied the economics and the soil conservation effects of combining pasture and cropland in rotations. Their interest in sod-based rotations began in response to the risk of erosion on continuously cultivated cropland. Leading farmers began to rehabilitate the land by establishing pastures and then by rotating in crops after the pasture. Initially, these sod-based rotations included conventionally tilled crops. Organic matter levels rose as high as 4% during sod years and decreased as low as approximately 3.3% during the cultivated crop years (Garcia-Préchac et al., 2004). In contrast, continuous cropping resulted in a steady decline in soil organic matter from 3.5% in 1962 down to approximately 2.8% in 1990. Bulk density of these soils began at 1.12 g/cm^3, rose to 1.28 g/cm^3 after 4 years of crops, and dropped back to 1.2 g/cm^3 after 3 years of grass (Garcia-Préchac et al., 2004).

This study showed a significant economic advantage to sod-based rotations because of lower nitrogen fertilizer inputs, higher productivity, and a gross income that was similar to or higher than that of continuous cropping. The mean gross income (profit after variable costs) was $120 per acre for the sod-based rotation and $70 per acre for continuous cropping (Garcia-Préchac et al., 2004).

A characteristic of sod-based rotations using conventional tillage is the roller coaster effect as soil organic matter rises during the grass cycle and declines during the crop cycle. To address this effect, researchers in South America and in the Southeast U.S. have been looking at rotating sod with no-till crops. Under this no-till system, residue decomposition is reduced and soil organic matter levels are maintained during the cropping portion of the rotation (Garcia-Préchac et al., 2004). Table 1 shows the effect of no-till vs. conventional tillage on erosion losses, carbon change, and relative yields from studies in Uruguay.

Table 1.─Erosion, yield, and soil carbon in sod-crop rotation

Adapted from Garcia-Préchac et al., 2004

Cropping system	Soil loss[1] (tons/acre)	Relative yield– 1st cycle (%)[2]	Relative yield– 2nd cycle (%)	Soil organic carbon (tons/acre)
Continuous crop (conventional)	8.5	NA	NA	15.2
Continuous crop (no-till)	1.3	96%	106%	18.7
Crops-pasture (conventional)[3]	3.2	100%	100%	16.5
Crops-pasture (no-till)	0.7	96%	120%	18.3

[1]Mean soil losses for two sites.
[2]Cycle of rotation included 4 years of crops (1st cycle), 4 years pasture, and 4 years of crops (2nd cycle).
[3]Crops-pasture (conventional) is 100% relative yield.

Transition from pasture to no-till

The above results show the advantages of using conservation tillage in conjunction with sod-based rotations, but conversion to no-till raises a few concerns that need to be addressed. One area of concern noted by researchers in Uruguay was infestation of bermudagrass (*Cynodon dactylon* [L.] Pers.) into cool-season grass. When the sod was killed chemically (with glyphosate), some of the bermudagrass survived and competed with the crop. This competition explains the relative yield of 96% in the first cycle of crops after grass (table 1). By the second cycle, the bermudagrass was under control and there was more fallow time between killing the sod and planting the crop. The researchers compared 15 days fallow time after killing sod to 70 days fallow time. Wheat yields were 22.3 and 46.3 bushels/acre, respectively, and nitrate levels in the top 6 inches were 10 and 35 ppm, respectively (Garcia-Préchac et al., 2004). When no-till crops are grown after sod, plenty of time is needed for dead sod to mineralize and release nitrogen prior to planting. Applying nitrogen starter fertilizer would lessen this concern.

Another concern associated with converting any cropping system from conventional tillage to no-till is a pre-existing plowpan. The no-till system inherits the problem. The problem can be eliminated eventually by root growth, enhanced biological activity, and increased organic matter from the increased root growth and reduced tillage of sod-based rotation systems.

Compaction from grazing

In addition to tillage, grazing is another potential source of compaction in sod-based systems. A study in the Georgia Piedmont showed some compaction associated with grazing but less than that produced by machine traffic in haying operations. Compared to hayland, bulk density (BD) was lower in grazed pasture at 0–0.8 inches but higher at 0.8–1.6 inches. In the top 2.4 inches, unharvested grassland had the lowest BD, grazing land was intermediate, and hayland tended to have the highest BD. This study showed that cattle at densities of 2 to 4 head per acre continuously grazing bermudagrass for 4.5 months in the summer did not contribute to excessive soil compaction (Franzluebbers et al., 2001).

Table 2.─Surface residue and soil organic carbon under grazed and hayed bermudagrass (Franzluebbers et al., 2000)

Property	Grazed	Hayed
	Carbon (tons/acre)	
Surface residue	0.8	0.5
Soil (0-5 cm)	8.2	6.0
Soil (5-12.5 cm)	5.3	4.7
Soil 12.5-20 cm	3.4	3.1
Soil total (0-20 cm)	17.0	13.9
Total carbon (surface residue and soil)	17.8	14.4

Franzluebbers and Stuedemann (2003) reported variations in bulk densities for different land uses. At a depth of 0–8 inches, BD was 1.38 g/cm^3 under 50-year-old grazed tall fescue pasture, 1.52 g/cm^3 under 40-year-old hayed bermudagrass, and 1.57 g/cm^3 under 24-year-old conservation tillage cropland. The lower bulk densities in grazing systems compared to haying systems are explained by soil carbon increases from the additions of manure as well as grazing management (table 2).

Other studies show more severe compaction from grazing, especially winter grazing of annual cover crops. Compaction from short-term grazing can inhibit the yield potential of subsequent crops. Touchton et al. (1989) measured soil compaction on a sandy loam down to 20 inches after 7 weeks of grazing winter rye, resulting in an average corn yield reduction of 14 bushels/acre. Yields were much improved by subsoiling or using a paraplow prior to planting corn (table 3).

Similarly, studies of winter grazing of cover crops in southern Alabama showed yield-limiting compaction down to 4–6 inches on a sandy loam. A similar study showed compaction down to 5 inches on a silt loam in northern Alabama (Siri-Prieto et al., 2003). Noninversion, in-row subsoiling can alleviate the effect of compaction on the yield. Before using tillage to reduce compaction in grazing systems, farmers should assess the extent of compaction (NRCS, 2003).

Table 3.─Corn yield following grazed or ungrazed cover crop (Touchton et al., 1989)

	Tillage for corn					
Rye treatment	No-till	No-till, w/ in-row subsoiling	Disk	Chisel	Turn plow	Paraplow
	Corn yield (bu/acre)					
Grazed	57	65	46	60	66	77
Not grazed	82	87	69	72	71	73

Economics of sod-based rotations

Incorporating short-term grazing into cropping systems has financial benefits. Research in Alabama found that contract grazing of stocker cattle in early spring (up to 140 days) offered returns of $70 to $225 per acre (Bransby et al., 1999). In studies of annual crop production with short-term grazing of winter annuals, researchers found that in-row subsoiling (noninversion subsoiling to 20 inches) with no-till reduced the effects of compaction caused by winter grazing and increased the net return per acre over growing only a cash crop (tables 4 and 5; Siri-Prieto, 2004).

Researchers at the University of Florida used a working business model to predict the potential income of continuous cropping of cotton and peanuts compared to a 4-year rotation consisting of 2 years of grazing cattle on bahiagrass followed by peanuts and cotton. Costs and yields were obtained from interviews with farmers, researchers, and extension specialists. Based on the interviews, the researchers assumed a 50% yield increase from adding grass to the rotation (from 650 to 975 lbs of cotton per acre). The model predicted that a 200-acre farm would yield $5,000 per year growing continuous cotton compared to $22,000 per year under the 4-year rotation if the 2 years of sod were not utilized. When grass was sold in rectangular bales the first year and grazed in a cow/calf operation the second year, the 200-acre farm yielded $31,000 per year (Marois and Wright, 2003).

Table 4.—Return per acre–peanuts

Stockers grazed on oat forage. Forage was cropped annually with a peanut-cotton rotation in southern Alabama. Returns are averaged over 3 years. (Siri-Prieto, 2004).

Tillage	Peanut yield (tons)	Peanut net profit ($)	Animal net gain ($)	Total ($)
Chisel	1.75	13	75	148
Paratill[1] + no-till	1.71	65	75	160
KMC[2] + no-till	1.84	105	75	180
No-till[3]	1.02	-51	75	18

See footnotes at end of table 5.

Table 5.—Return per acre–cotton

Stockers grazed on ryegrass or oat cover crops. Forage was cropped annually with a peanut-cotton rotation in southern Alabama. Returns are averaged over 3 years. (Siri-Prieto, 2004).

Tillage	Cotton yield (lbs)	Cotton net profit ($)	Animal net gain ($)	Total ($)
Chisel	3,006	256	75	331
Paratill[1] + no-till	3,120	288	75	363
KMC[2] + no-till	2,987	263	75	338
No-till[3]	2,261	129	75	204

[1]Paratill is a bent-leg subsoiler.
[2]KMC is a straight-shank subsoiler.
[3]No-till without noninversion is not normally recommended on soils that are compacted on a recurring basis.

Conclusions

Sod-based rotations help to control erosion, increase soil organic matter, and offer diversity, which helps to control diseases, insects, and weeds. The increased diversity and soil organic matter tend to improve productivity of crops grown in rotation with sod. In addition, the roots of sod improve the rooting depth for annual crops, thus reducing compaction and drought stress. Grazing systems can lead to surface compaction, especially on some soils that are grazed in winter. If no-till is integrated into sod-based rotations, many benefits of sod are preserved through the cropping phase of the rotation. After the grazing component of the rotation, farmers should measure for soil compaction prior to planting the next annual crop. Also, the farmers should provide plenty of time between killing the sod and planting the next cash crop to allow for N mineralization. Short-term grazing can supplement the income of sod-based rotations. These rotations are not for everyone but may be effective on farms that already have livestock or are in areas of marginal soils where annual cropping systems are economically and environmentally risky.

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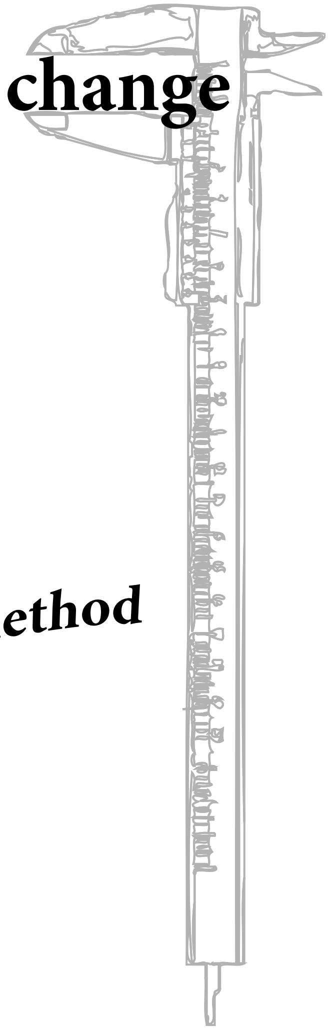
Measuring soil carbon change



A flexible, practical, local method

Peter Donovan

version: October 2013

Contents

What this guide is about, and how to use it

> Do civilizations fall because the soil fails to produce—or does a soil fail only when the people living on it no longer know how to manage their civilization?
>
> Charles Kellogg, "Soil and Society"

This short guide is for people who are interested in the possibilities of turning atmospheric carbon into soil carbon. It is about gauging fundamental biosphere function at specific locations. It is about monitoring: why, how, and what.

Most previous writings on the subject have treated the measurement of soil carbon primarily as a technical issue, requiring a high level of knowledge and expertise, and were focused on verifying greenhouse gas "offsets" or selling carbon credits, either in existing or anticipated markets.

This guide is different. Soil carbon measurement is as much a social issue, involving beliefs and attitudes, as it is a technical one. This guide does not offer approved methods for verifying greenhouse gas "offsets." Nor does it contain specific advice about which agricultural practices, technologies, or species might be best at building carbon in the soil, or predictions about the global effects of such practices. However, the monitoring practices outlined in this guide will be useful in developing site-specific answers to these questions.

There are many contexts and ways of thinking about soil carbon, and different perceptions on its importance. How you measure something depends on your purpose, and this guide aims to accommodate a spectrum of purposes. Are you wanting to know if your lawn, farm, or ranch is turning atmospheric carbon dioxide into water-holding, fertility-enhancing soil organic matter, or the reverse? Are you wanting to show what's possible with management? Are you trying to convince yourself, or others, that the changes you are working toward with your land management are having an impact on soil carbon?

Much of world agriculture has long depended on purchased inputs of nitrogen, potassium, and phosphorus. Carbon, the principal dry-weight constituent of crop residue and manure, has typically been regarded as a waste product and a disposal problem, to be dumped somewhere else, or burned.

More and more people have been pointing out that soil carbon "sequestration" could offset fossil fuel emissions, with plenty of other benefits besides. It's no surprise that there's resistance, power struggles, and confusion around the increasing emphasis on soil carbon. There has been lots of research and prediction, but very little in the way of monitoring local changes over time, and relatively little change in agricultural incentives or policy.

Government and agricultural experts have been saying that soil carbon is too hard or too expensive to measure because of its variability and complexity, and that the only practical way to get a handle on what is happening with carbon in soils, or to design the proper incentives, is computer modeling based on standardized agricultural practices, aided by remote sensing.

This guide aims at a different approach, which has been developed for the Soil Carbon Challenge (see page 35). Variability and complexity are not the enemy, but the raw materials for creativity and innovation, for enhancing biosphere functions and letting the solar-powered plants, microbes, and animals do more of the work.

This guide attempts to cut through some of the confusion and technical trappings that have accumulated around the subject of soil carbon, soil carbon change, and its measurement. It attempts to provide a monitoring method that is both flexible—that can be adapted to a variety of purposes and situations—and practical.

Depending on your purpose, measuring change in soil carbon need not be difficult, and it need not cost much. The methods described here will enable you to measure change in soil carbon with accuracy and confidence, using hand tools and established laboratories for accurate soil analysis. For a quick overview of what is involved, take a look at the checklist on page 39.

Even if you don't want to measure soil carbon change yourself, this guide will help you understand the process and some of what is at stake.

In developing this guide (an ongoing process) I am indebted to many dedicated and hardworking people, who have both taught me some possibilities about measuring soil carbon, and have helped me understand the questions, methods, possibilities, contexts, and limitations both of the soil carbon opportunity, and in our ways of thinking about it. In addition, the approach and methods advocated here owe much to previous publications, such as Ellert, Janzen, and Entz 2002, and most of which are listed in the references.

Peter Donovan
soilcarboncoalition.org

1

The work of the biosphere

> Life is the most powerful geologic force.
>
> Vladimir Vernadsky

In the 1920s, the Russian geochemist Vernadsky recognized that the composition of the atmosphere results from the metabolisms and choices of the biosphere's self-motivated and autonomous organisms, from bacteria to humans.

At the time, there was little demand for this kind of understanding. But it is increasingly obvious that the decline in biosphere function worldwide is accelerating. The composition of the atmosphere is changing, with reduced transparency to the radiation of heat into space. With atmospheric change comes increasing acidity in the oceans.

1.1 Technology

> Institutions will try to preserve the problem to which they are the solution.
>
> Clay Shirky

Though we may recognize our dependence on the biosphere, we tend to view it as a somewhat static environment, vulnerable to our greed and technology, in need of protection. The problem-solving environmentalism of the last two generations has worked on protecting nature from harm and pollution: regulating, limiting, and changing our technology.

But it's not working very well. Even ceasing to burn fossil fuels altogether won't solve the atmospheric carbon issue.

The biosphere is the sum of all the living and the dead. It doesn't just sit there looking pretty, wild, or vulnerable. It does work, a lot of it. In addition to the enormous deposits of fossil fuels whose oxidation currently powers our civilization, the biosphere's résumé includes the calcium carbonate rocks that cover a tenth of the earth's surface, banded iron ore formations that supply our steel, much of ocean chemistry, soils that feed the world, peat formations, and the composition of the atmosphere. Current responsibilities include feeding everybody, capturing and holding soil moisture for land dwellers, and all the rest of what are called ecosystem services.

The issue is not just technology, though it plays a large role. The issue is that, over vast areas of the world, **the biosphere is not doing enough work.** With livestock confined, and crop monocultures dependent on fossil energy to maintain them, too many of the animals are in prison, too many of the plants are on welfare, and too many of the microbes are dead.

Work is force over distance, getting things done. Most of the biosphere's work is done through the chemistry of photosynthesis. Solar powered, this work converts inert carbon dioxide into food for all life.

1.2 The carbon cycle

> Humus plays a leading part in the storage of energy of solar origin on the surface of the earth.
>
> Selman Waksman, 1936

The pattern and process of this work is the carbon cycle. Carbon is life and food, and moves from atmosphere to plants and soils and back in a grand cycle that is sometimes called the circle of life. This circle encompasses both the living and the dead. The biosphere, idled as it is, still moves 9 times the carbon, and does 9 times the work, of all fossil fuel burning.[1]

Without carbon cycling, and the growth of living tissue, there wouldn't be anything to slow down water. Rains would wash soil into the sea.

The hub of the terrestrial carbon cycle, containing more carbon than atmosphere and forests combined, is soil organic matter. Soil organic carbon is a result of ecological processes occurring at or near the soil surface, such as energy flow, mineral cycling, water cycling, and community dynamics. But it also enhances these same processes, absorbing and slowing down water, supporting energy flow, supporting enormous microbial diversity, retaining minerals for plant use, and improving soil quality. Soil organic matter is one form of the surplus thermodynamic work of the biosphere, the excess of photosynthesis over respiration. Fossil fuels are another.

Because soils hold more carbon than the atmosphere and vegetation combined, and can hold it longer, people are increasingly looking to soil carbon as an opportunity to both mitigate and adapt to climate change, along with its twin issue, ecosystem function. Grasslands are not just empty spaces for producing livestock, or flyover land between urban economies. They have a major influence on the composition of the atmosphere, with greater leverage than fossil fuels because they can accumulate carbon, not just release it to the atmosphere.

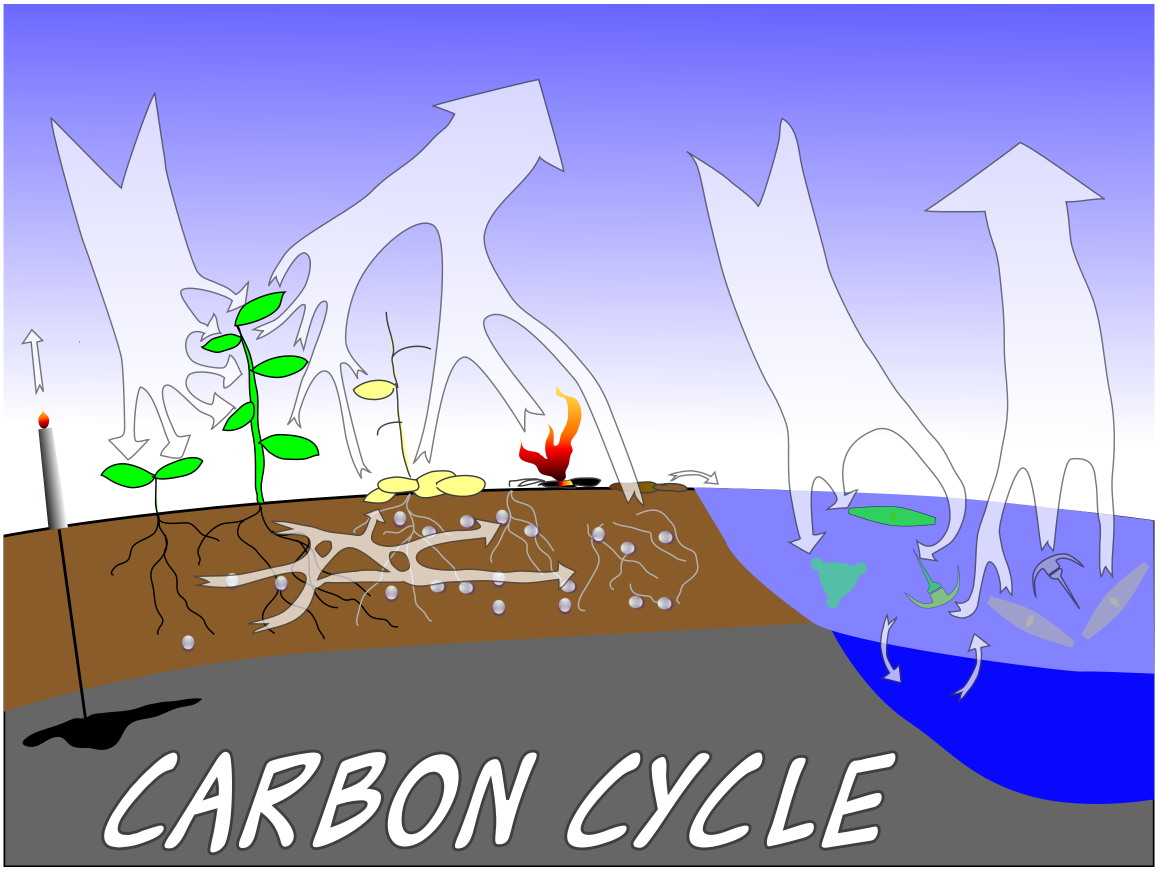


Figure 1.1: The major flows of carbon in the biosphere. Fossil fuel burning (far left) represents only about 4 percent of the annual flux of carbon dioxide to the atmosphere. The geological carbon cycle is likewise just a small bit of the huge cycle of carbon driven by photosynthesis and biology. (See Rattan Lal, Sequestration of atmospheric CO_2 in global carbon pools, *Energy and Environmental Science* 1, 86–100 [2008].)

1.3 Let, not make

> We want to *make* animals do things. My whole theory is, I *let* animals do things. Anytime that I need an animal to do something, if I position myself properly, I can let it do it. It's doing what it wants to do, it's doing what I want it to do, so we can both be happy. Anytime that you go to make an animal do something, you create some problems that you don't need.
>
> Bud Williams

The work of the biosphere is accomplished by self-motivated, autonomous organisms: plants, bacteria, animals, humans, and all the rest. The more we can move from *make* to *let*, the better off we'll be, including when we're trying to change people's beliefs or behaviors.

In our attitudes, we are deeply attached to *make*. We're addicted to solving problems, which then multiply. What we need to do is to make our decisions so that these problems fade or disappear.

Some of the most successful and creative farmers and ranchers let their animals, plants, and microbes do the work. They're weaning themselves from *make*, from the addiction to materials handling and more and more technology. They don't spend time and energy making soil bare of life. On these farms and ranches, the biosphere is doing more and more work. There is more photosynthesis going on, for longer seasons, with more diversity, and the release as oxidation is slower.

One of the reasons that our soils have lost so much organic matter (carbon to the atmosphere) is that we have not let them store it or accrue it. The biosphere can turn atmospheric carbon into water-holding, fertility-enhancing soil organic matter, if we let it.

And with monitoring of soil carbon change, we can let the people who know how to let this happen, show us how it is done.

1.4 Monitoring: a strategic and creative choice

> There is a fundamental mismatch between the nature of reality in complex systems and our predominant ways of thinking about that reality.
>
> Peter Senge, *The Fifth Discipline*

When we don't have a grasp of the existing situation or of its variability, it's tempting to attribute routine occurrences to special causes. Traffic slowdowns, for example, can happen on an urban freeway for no other cause than natural variations in driving speed and spacing.

Properly designed, repeated observations over time can help distinguish the effects of management from those resulting from weather or just normal background variability. Such observation can enable managers to work with, rather than against, underlying ecosystem processes. Instead of merely responding to short-term events or trends, managers guided by good monitoring can strategically enhance these underlying processes, which can increase economic viability and sustainability as well as leadership in policy and research.

Ecological monitoring has two functions:

1. early warning of opportunities and hazards (navigating toward goal by looking ahead through the windshield)

2. checking to see what happened, and tabulation of results and demonstrated possibilities (rearview mirror)

Monitoring is a relatively rare, somewhat hybrid activity that occupies the space between (and is sometimes confused with) two multibillion-dollar giants: prediction, which typically uses computer models to predict future conditions; and research, which typically checks to see what happened after an activity.

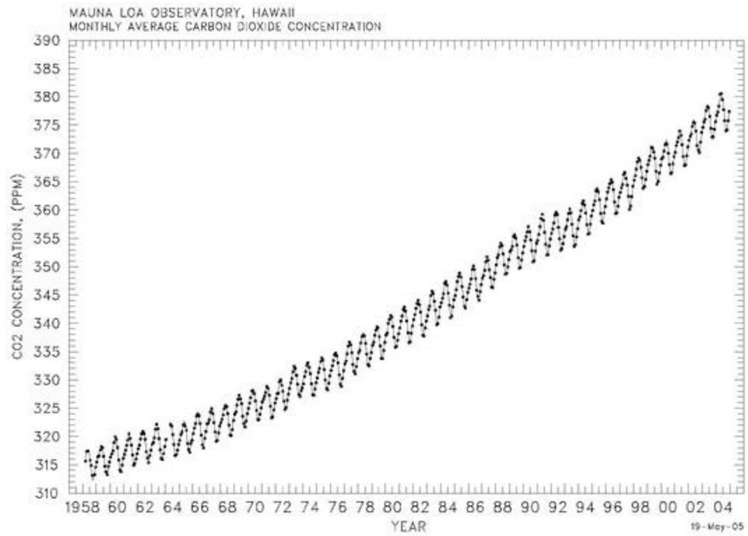


Figure 1.2: The Keeling curve of rising atmospheric carbon dioxide, which is a trace gas in Earth's atmosphere but the predominant one in the atmospheres of Venus and Mars. Wrote Keeling in 1998, "Environmental time-series programs have no particular priority in the funding world, even if their main value lies in maintaining long-term continuity of measurements."

Governments and corporations demand predictions today, much as people demanded astrological forecasts in the Middle Ages. But the best way to predict the future is to create it. Monitoring is a navigational aide for this that also records a track, like a GPS (global positioning systems) receiver.

Of course monitoring must be part of a larger cycle, called plan-monitor-control-replan, or as W. Edwards Deming put it, plan-do-study-act.[2] In the latter version, monitoring is the study part of the cycle, connecting do and act. Monitoring adds tremendous value to grazing planning, to testing decisions, to financial planning. (In far too many of our organizations and institutions, the parts of this cycle have been separated into silos, where planning is a different department than doing, and study has little to do with action.)

The heart of monitoring is the attentive study of the here and now. The power and even creativity of this is often underestimated. In 1958 Charles David Keeling went to great lengths to establish an accurate monitoring program for atmospheric carbon dioxide (Fig. 1.2). His core enterprise was not research—he was not attempting to determine the causes of change—nor prediction. Yet his monitoring work, which often struggled for funding against sexier research and prediction and was regarded as routine, resulted in the Keeling curve of jaggedly rising carbon dioxide in the atmosphere, which continues to frame the entire climate issue and influence people's attitudes and beliefs in ways that research, prediction, or argument cannot.

Monitoring, and letting good things happen, encourages us to be

1. observant

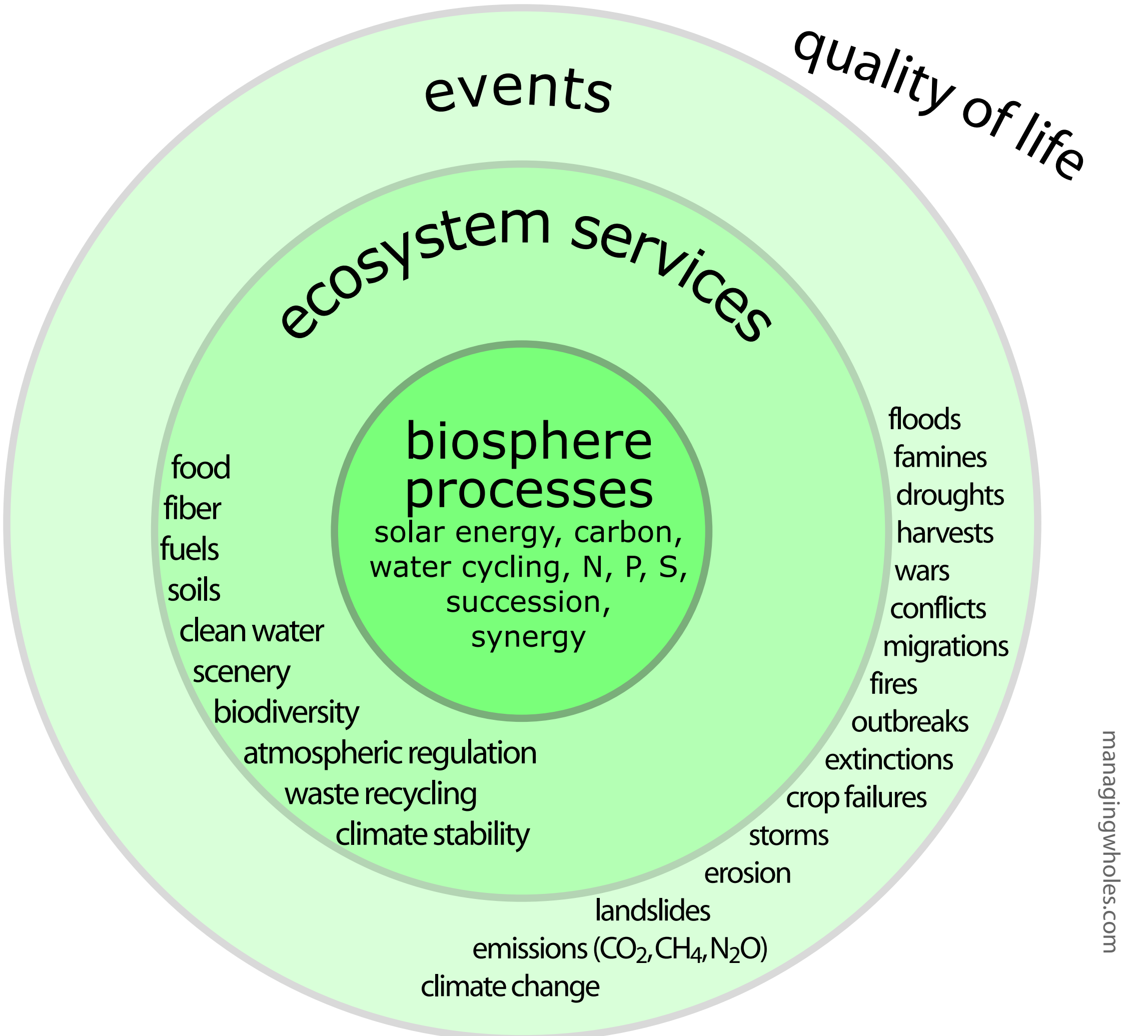


Figure 1.3: On which level do we typically focus our efforts? If we want to transform the situation, where is the center of gravity? Where can self-reinforcing or positive feedback create fundamental shifts?

2. empathetic, understanding and empathizing not only with mammals or other organisms, but with the biosphere's underlying processes such as water cycling, carbon cycling, and solar energy flow

3. aware of our position or influence relative to the issue or process we are trying to address (don't stand in the way)

Soil carbon, which can be measured accurately, may be one of the easiest and most practical ways to monitor the **work of the biosphere** on land, on which our climate, water cycling, and welfare depend. By monitoring this biosphere function locally, we can show what the possibilities are in our back yards, towns, farms, ranches, and open spaces.

2

Measuring soil carbon

> If they can get you asking the wrong questions, they don't have to worry about the answers.
>
> Thomas Pynchon, *Gravity's Rainbow*

Like the atmosphere or the oceans, soil is a complex three-dimensional layer whose composition results in good part from the metabolisms and choices of the biosphere's self-motivated, autonomous organisms, along with physical influences such as the parent material, climate and weathering, and water.

But soil is not as well mixed as are the atmosphere or oceans. It is a product of history, much of it local, on the scale of millimeters as well as miles. Variability is everywhere.

2.1 Purpose, result, and uncertainty

There is no right or wrong way to measure soil carbon. **What** you measure, along with **how** you measure it, depends on your purpose—**why** you are doing it, and what you are going to do as a result. The questions you are trying to answer will depend on the purpose. So do the likely sources of uncertainty or risk.

Some people may have mixed or multiple purposes, or may be measuring soil carbon change for other reasons than what are listed here. Here are four of the most common results from (or purposes for) measuring soil carbon change.

1. Do nothing. Some people measure soil carbon just for curiosity, or research for its own sake, and don't make any changes as a result.

2. Sell something such as carbon "offsets" or ecosystem services. Common questions include: How many tons of carbon or carbon dioxide per hectare per year? How certain can we be of the estimate? How permanent is the sequestration?

Sampling error and biased or non-random selection of sampling sites can be sources of uncertainty. Statistics based on frequency probabilities may be your main tool for gauging or quantifying such uncertainty, and for designing a sampling scheme that meets the need for statistical credibility. The statistics chapter may be helpful.

However, there are other sources of uncertainty in selling carbon credits or ecosystem services, such as whether these markets exist or will exist, whether you are eligible to participate, present and future prices, overhead or transaction costs, and other verification requirements such as adhering to certain land management practices, or to certain standards of documentation. Compared to these additional sources of uncertainty or risk, statistical uncertainty over tonnage of carbon sequestered may turn out to be minor.

3. Test agricultural or land management practices, and use the results to set policies or incentives for best management practices. Which are the best management practices for sequestering carbon, and how much carbon do they sequester? What will effective incentives consist of, and how can can they be created?

With this purpose, statistical uncertainty over tonnage, to which experimental design and randomized sampling contribute, can be significant.

There is also uncertainty around whether the practices you are experimenting with can be accurately defined. The term *grazing*, for example, can describe a huge range of activities with many variables, each with high variability. Are we talking about insects, rodents, single-stomached mammals, ruminants, or some combination? Time and timing? One or one million pounds of grazing animals to the acre? Animal behavior and dietary selection vary greatly. The full range of possibilities or variables isn't listed anywhere. Things change. Future possibilities may differ from past experience. Some farming practices may be easier to describe, but when you are defining or prescribing practices, large difficulties of interpretation remain.

The definition issue increases the uncertainty about the causes of change in soil carbon. Is it variation due to normal fluctuations in microbial activity, weather, or combinations of these, or some unknown causes, or is it caused by the management practices under investigation?

When "best management practices" are chosen or defined, you forgo adaptation to changing conditions and situations. If the practices work for a while, and then quit working, or simply don't work in some areas or conditions, incentive programs may be slow to change.

In designing incentives, uncertainty about the behaviors and beliefs of land managers looms large. Cost, technology, and the broad spectrum of cultural and cognitive biases are not always predictable. How well the chosen best management practices perform in other areas or regions, or how they are implemented with varying degrees of skill, insight, or commitment—the uncertainty here can be huge.

Many of these uncertainties arise from the attempt to define or prescribe best management practices for others, which characterizes a great deal of agricultural research. When measurement of soil carbon change is used as feedback to management, or monitoring, as in the following strategy, many of these uncertainties can be managed.

4. Test specific, local management, and use the results to learn and innovate toward a desired future, both locally and globally. How might our management of this land create the future that we want? What other considerations apply?

As with previous strategies, statistical uncertainty will play a part, as will experimental design, location of plots, and the choice of boundaries on the vertical or horizontal strata in your sampling design.

In analyzing soil carbon change, separating normal from special causes of variation can be difficult, and statistical analysis is only partly helpful.

Major sources of uncertainty include your beliefs about what's possible, how good your decision making is in relation to the desired future you want to create, your ability to test decisions well, your observational skills, and your willingness to question or test your beliefs.

However, someone who is monitoring his or her own management has a tremendous advantage over the researcher looking for best management practices. This is the opportunity to **take responsibility** for creating the results, for creating a desired future, along with the responsibility for his or her own beliefs, commitment, and skills. The manager can commit to flexible management, to adapting and innovating based on what monitoring indicates, including early warning signs of shift in the way biosphere processes are operating.

§

In the results or purposes enumerated above, there is a progression from the enumerative (counting tons of carbon) to the predictive (best management practices and their yield of soil carbon) to the creative (testing and innovating in a specific situation).[3] Moving from enumerative to predictive to creative means accepting more and more responsibility, which also gives you increasing opportunities to manage and reduce uncertainty and risk.

Though measurement of soil carbon has so far been treated mostly as a technical or statistical problem, the main sources of uncertainty in achieving common purposes and objectives are human and social—such as people's beliefs about what is possible or not possible. Grasping the soil carbon opportunity is a people issue, not just a technical one.

2.2 Change

Any practice that improves soil structure is building soil carbon.

Christine Jones

Enormous efforts have been devoted to mapping and classifying soils as if they are unlikely to change very much on a human time scale. *It takes a thousand years to form an inch of soil* has been repeated so often that it is regarded as true by many. Charles Kellogg, who in the 1930s was soil survey chief for the U.S. Bureau of Chemistry and Soils, wrote:

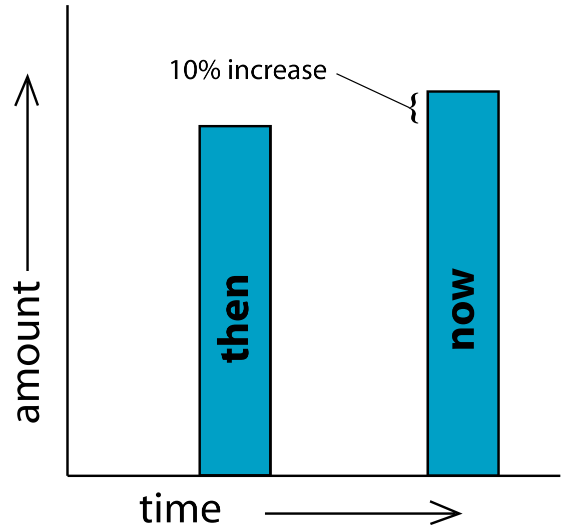


Figure 2.1: Measuring soil carbon change is **simple.** It requires 1) two samplings or measurements of the same soil area, at different times; 2) accurate sampling and laboratory analysis; and 3) more than just one or two samples; 4) commitment and patience, as the *then* must be established well before the *now.*

> Some people speculate about how much time is required "to build an inch of soil material." The answer could well be, "somewhere between 10 minutes and 10 million years."

Today, many people are becoming more concerned with the possibilities for **change**: preventing loss of soil organic matter, and creating positive changes through management. Most research, however, has leaned toward comparing two areas with different management histories, rather than monitoring one place over time.

This guide is directed at monitoring. It shows how to set one or more benchmarks or fixed plots from which a time series of multiple samples can be taken and analyzed, in order to detect and measure change. In effect, a compact 4×4-meter plot serves as its own "control" in an experiment carried out by biosphere processes, human management decisions, and weather over time.

This is easier than mapping soil carbon over a field or land parcel, but it takes patience. Results are not instant. The longer you wait between samplings, the greater your chance of detecting and measuring change, and distinguishing the effects of management from those of year-to-year weather variability.

Soil carbon can be divided into various categories, and there are two commonly measured attributes:

1. **Trend**, or percentage change in soil carbon, to a given depth. Sample declaration: in three years soil carbon percentage in the top 30 cm has changed from 1.9% to 2.7%, a relative gain of 42%, or 12.4% per year on average, compounded for three

years. Conclusions about trend in soil carbon require measurement of only one parameter: carbon percentage in soil.

2. **Mass**, quantity, or tonnage of soil carbon, per hectare or per acre, to a given depth. Sample declaration: in three years this area, plot, or field has added 4.2 tons C (equivalent to 15.4 tons CO_2) per hectare to a depth of 30 cm, or 1.4 tons C per hectare per year. Conclusions about mass or quantity of soil carbon require measurement of two parameters: 1) carbon percentage of soil, multiplied by 2) bulk density of soil (dry mass per unit volume). This multiplication converts percentage carbon to mass.

Because of variability combined with relatively small sample sizes, both types of measurements result in statistical estimates, qualified by standard error ($\pm$ error) and probability or confidence (for example, $p \leq .05$ or 95% confidence).

For purposes of feedback to management, or establishing that management is storing more soil carbon, or for progress in soil quality, trend may be all you need. See `soilcarboncoalition.org/changemap.htm` for some examples.

The policy and "offset" market discussions have focused on mass, quantity, or tonnage of carbon or carbon dioxide. Detecting change in soil carbon mass, since it requires measurement of three parameters (carbon percentage, volume sampled, and bulk density) is more complicated.

Voluntary or local carbon market transactions or incentives may be more likely if you measure mass. Should regulated markets emerge, there is no guarantee that the methods outlined here would be accepted as verification.

2.3 Organic and inorganic soil carbon

The element carbon exists in the soil in many forms, but for the purposes of measurement and analysis there are three main forms.

Organic soil carbon is derived from living tissue: plant leaves and roots, sap and exudates, microbes, fungi, and animals. It takes a bewildering variety of complex chemical forms, many of which remain unclassified. Much of it is a result of decay processes and microbial metabolisms. Soil organic matter is a generic common name. It contains 50–58 percent carbon by dry weight.

Soil organic matter holds many times its weight in water. Its critical sticky components (such as glomalin) play a critical role in the formation of soil aggregates which give soil its stability against weathering and erosion, and its ability to hold water and air for plants and microbes.

The number one recommendation of the USDA-NRCS Soil Quality Team is to enhance soil organic matter (`http://soils.usda.gov/sqi/`).

Soil organic matter may be the most valuable form of soil carbon, but is generally the least stable, though some forms may persist for a thousand years or so. Many forms can be readily oxidized (turned into carbon dioxide) by common bacteria in the presence of oxygen. But it is also the form of soil carbon that can readily increase as a result of plant growth, the root shedding of perennial grasses, the incorporation of manure or compost, the liquid carbohydrate exudates of plant roots, all processed by microbial metabolisms. Soil organic matter is the most abundant form of soil carbon.

Charcoal also derives from living tissue, so it is considered organic. It is often called biochar. It can range from 50 to 95 percent carbon by weight. It is more stable and more resistant to bacterial oxidation than most other forms of organic carbon, which is one reason why there is considerable interest in incorporating biochar into soil as a carbon sequestration strategy.

Inorganic soil carbon is mineralized forms of carbon, such as calcium carbonate ($CaCO_3$) or caliche. It is more stable than most organic carbon because it is not food or fuel for microorganisms. Because acid dissolves calcium carbonate, it is not usually abundant in soils of pH 7 or lower, or in humid regions. Carbonates are common in more arid regions and alkali soils, and are a significant soil carbon pool worldwide, derived mostly from organic carbon fixed by photosynthesis.

Inorganic carbon, while it does not possess the water-holding and soil-enhancing properties of organic carbon, is nevertheless a significant sink for atmospheric carbon, though it typically changes at a slower rate.

2.4 Laboratory tests

Soil carbon cannot be measured directly. However, some methods are far more direct than others, and involve fewer assumptions and sources of error. Though there has been considerable buzz about the possibilities of remote sensing or high-tech field methods of assessing soil carbon, and some of these show promise, the gold standard remains careful, repeated field sampling followed by laboratory analysis by the dry combustion method, often called elemental analysis.

The dry combustion or elemental analysis procedure is the most accurate common test for soil carbon, and is often cheaper than other tests. Most research indicates that change in soil carbon occurs most readily in the soil organic matter fraction, so that if you detect change, it is likely to be in the organic carbon.

However, if carbonates are a significant percentage, your ability to detect change will be better if you have at least some idea of how much soil carbon is organic and how much is inorganic.

Dry combustion or elemental analysis. The most accurate standard laboratory test for soil carbon is dry combustion using an elemental analyzer such as those made by Leco, Perkins-Elmer, Elementar, or Carlo Erba. These instruments heat a small sample (usually a fraction of a gram) of dry pulverized soil to around 900° C and measure the CO_2 gas that is a combustion product. (They usually measure nitrogen as well.) The results are expressed as the percentage of carbon in the sample. The dry combustion test oxidizes and measures total soil carbon: organic matter, charcoal, and carbonates. (There is a short listing of U.S. soil labs on page 32.)

Acid treatments. If the soils you are testing contain carbonates or inorganic carbon, and you wish to distinguish organic and inorganic carbon, many labs have an acidification option, in which a sample or subsample is treated with hydrochloric acid to remove carbonates, and then subjected to dry combustion to measure remaining organic carbon. Measuring organic and inorganic carbon separately thus requires acidification plus two dry combustion tests.

Loss on ignition and Walkley-Black. Less accurate are the more traditional loss on ignition (LOI) and Walkley-Black tests. Loss on ignition measures the weight loss of a dry soil sample after it is heated in an oven or muffle furnace to 360–450° C for a couple of hours. Walkley-Black is a wet chemistry method using potassium dichromate.

Neither of these tests measure total carbon. The Walkley-Black test does not usually give a full accounting of charcoal, and may miss some types of organic matter. Neither measures inorganic carbon.

The interest in soil carbon from the perspective of biosphere function or climate change is relatively recent. Many labs are accustomed to testing for soil organic matter for the purposes of calculating effective rates of herbicide application. For this purpose, soil organic matter is a liability because it lessens the effectiveness of herbicides on living vegetation, and loss on ignition or Walkley-Black tests are typically used.

Carbon fractions. Recently there has been increasing interest in classifying various types or fractions of soil organic carbon such as active, labile, particulate, occluded, light, or heavy, with various residence or turnover times ascribed to the various fractions. Ray Weil and others have recently promoted the use of potassium permanganate wet chemistry to measure active carbon in soil, which may give an earlier indication of soil carbon change.

Soil respiration. Soil respiration, the emission of carbon dioxide by microbial respiration, is a good indicator of microbial biomass, but may not correlate well with soil organic matter or total carbon. `solvita.com/soil` sells a few types.

Bulk density. The density of soils can vary over a wide range. Water has a density of 1 gram per cubic centimeter. Soils can have densities ranging from .1 for light peats to 1.8 for very dense, compacted mineral soils, often with little pore space for water and air. Organic matter is lighter than most mineral matter, so if organic matter increases in a soil, the density will likely decrease.

The test for bulk density is simple: oven-dry a sample of known volume to remove all moisture, and weigh it. The bulk density is the dry weight in grams divided by the volume in cubic centimeters.

form or aspect of soil C	tests	comment
organic C	dry combustion (prior acidification of sample will remove inorganic carbon), loss on ignition, Walkley-Black, soil respiration, active carbon tests	the largest and most important soil carbon pool
inorganic C (carbonates)	dry combustion (with organic carbon subtracted)	an important soil carbon pool, but slower to change
charcoal	dry combustion, Walkley-Black (partial)	recalcitrant form of organic matter
total carbon	dry combustion	for most purposes, dry combustion is the best and most accurate test
bulk density	oven-drying and then weighing a sample of known volume	essential to be able to quantify mass or tonnage of carbon in soil

2.5 Getting started

The forms of carbon you choose to measure **depend on your purpose.** The carbon cycle involves all forms, some slower, some faster. Measurements of net gain or loss of total carbon in soil can show the overall picture, but will not distinguish the forms and pathways.

Depending on purpose, some of the material in this guide may not apply. The main difficulty with any monitoring program is getting started. The best time to start monitoring is typically 10 or 20 years ago. The second best time is now.

1. Set up and sample one or more fixed plots or benchmarks now (see chapters 3 and 4). You can add more later.

2. Use the dry combustion test (CN analyzer) for analysis of total soil carbon.

3. Use the metric system as much as possible. It's easier to compare your figures to those of others, and some calculations are much easier.

3

Site selection and sampling design

> The most meaningful indicator for the health of the land is whether soil is being formed or lost. If soil is being lost, so too is the economic and ecological foundation on which production and conservation are based.
>
> Christine Jones

Because this guide focuses on measuring **change** in soil carbon, it recommends a system of fixed plot locations, in which multiple samples are taken. The idea is not to map soil carbon, but to establish benchmarks, indicator plots, or experiments by which change over time can be detected.

3.1 Mapping your site

There are many advantages to online mapping. Google Earth is a free program that allows you to draw lines, polygons, and points, see topography, and save and share your maps with others. For the U.S., range, township, and section boundaries and USGS topographical maps can be added as overlays. You can also map points and tracks that are recorded by a GPS receiver. There are free utilities that can calculate the area of polygons or boundaries from the .kml (keyhole markup language) files that Google Earth uses.

Geographical information system software (GIS) can also be used, but sharing is more limited.

Paper maps are durable and versatile. A map is not the territory, but a map, even a hand-drawn one, is better than no map for marking land divisions and plot locations.

3.2 Stratification

The purpose of sampling is typically to get useful data, with the appropriate resolution and confidence, while holding down costs. Stratification, the division of the soil to be sampled into layers or horizontal zones likely to have similar degrees of change, may give better resolution and confidence without increasing the number of plots, and thus costs. For an example of how to process data from horizontal strata, see page 47.

A stratified sampling approach is most effective when three conditions are met:

1. variability within strata is minimized
2. variability between strata is maximized
3. the variables upon which the parcel is stratified (such as slope, vegetation cover, or management) are strongly correlated with soil carbon change

Vertical strata

Soil carbon is likely to vary with depth. Most soil carbon sampling thus defines one or more layers of soil, usually by the distance in centimeters from the soil surface.

For example, in a grassland where the average depth of dense roots is 30 cm, it may make sense to define the top layer as 0–30 cm, or further subdivide it into 0–10 and 10–30 cm layers. Separation into layers will affect your ability to detect change. The thinner the layer, the better the resolution—the ability to detect smaller changes. But thinner layers mean more complicated sampling, and higher laboratory costs.

Deeper layers may have less variation, but the tonnage of soil carbon can be significant below the surface layers. The liquid carbon pathway, by which plants exude photosynthetic compounds which are taken by mycorrhizae and then turned into humus by a variety of other microorganisms, may be pronounced in permanent grasslands. In sampling pastures at 0–10 cm, 10–25 cm, and 25–40 cm, I've often found carbon content higher in the 25–40 cm layer than in the 10–25 cm layer.

Horizontal strata

A peat bog is likely to have much higher carbon content than an arid upland soil. If it has been drained or partially drained, it may be losing carbon through oxidation, whereas the upland soil may be gaining carbon. Sampling these areas separately, as different strata, can significantly reduce the variability you encounter, thus boosting confidence and increasing resolution while not increasing the number of samples needed.

Differences in soil types, slope and aspect, vegetation cover, or management whether past or present may be good criteria for separating land into different strata. Mapping software, such as Google Earth, can help with this.

For the U.S., soil maps and reports for areas of 10,000 acres and under can be defined and then downloaded from the NRCS website:

`websoilsurvey.nrcs.usda.gov/app/HomePage.htm`

There are also soil survey layers for Google Earth, for example,

`casoilresource.lawr.ucdavis.edu/drupal/node/538`

3.3 Locating plots

The ideal in statistics is for sampling locations to be chosen at random, where each potential core sample location has an equal chance of being chosen. With small sample sizes, this is often not practical. Plots should be located in areas that are typical or representative of the stratum, or of the majority of the area you are dealing with. If you come to feel that one or more plots are badly located, you can establish others.

Plots should be representative of slope and aspect, and in hilly ground could include ridgetop, midslope, and bottom positions. Locating plots according to soil type can often work well for this.

Plots can also represent different management. For example, it may be instructive to locate a plot inside a grazing exclosure, so as to be able to compare the rate of soil carbon change under grazing management with that under rest from grazing.

It helps to think of plot selection as experimental design. How can you test your beliefs or hypotheses? It may even be possible to locate plots, or design an experiment, that tests beliefs that you don't even know you have.

It is a great advantage to combine soil sampling for carbon change with soil surface monitoring of biosphere function such as Land EKG or Bullseye. This will help you standardize plot locations as well as give you more results for your field time.

3.4 Sampling tools

Soil carbon can be most accurately measured by means of undisturbed samples, in other words intact cores that can be segmented by depth. Soil probes that cut a core are best for this. For rangeland and pastures, hand or hammer probes that have an open slot on one side tend to be easier to work with than probes that collect the sample within a plastic tube, because it is easier and quicker to detect gaps and clogs with a slotted sampler. The height of the slot limits the depth of your sampling. The rest of this guide assumes that you are using a soil probe that cuts intact cores.

Hand probes come in a variety of sizes and configurations. Some have a T-handle for pushing into the soil and others have various hammer attachments, such as a slide hammer, for harder soils. Some have replaceable tips, which are advisable with a hammer probe because you will hit rocks.

3.5 Sampling intensity within the plot

On unplowed grasslands, where variability tends to be high over short distances, 8 samples per plot are advisable in the surface layer. On regularly tilled ground, 4 samples per plot in the surface layer should be sufficient for most purposes. In forests, soil carbon variability can be very high because of buried rotting wood, and more samples should be considered.

Once you have decided on a sampling intensity for your plots, match your locations to the grid layout for consistency. For example, if you are taking 6 surface samples, 2 deeper samples, and 2 bulk density tests, you may choose to use grid locations 1, 4, 10, 19, 22, 25 for your surface samples, 10 and 19 for your deeper samples, and 4 and 22 for your bulk density samples.

The grid plot layout enables us to take multiple samples in a compact area, over multiple samplings, without resampling a previously disturbed hole. The mean or average carbon content of the plot provides a kind of benchmark for the plot area. We cannot in fairness resample the same soil on subsequent samplings, because of the potential effect of the disturbance on soil carbon content, but we can again take multiple samples from the same compact area, and thus estimate change over time for the plot.

If economics permits, you may wish to analyze core samples separately, for at least one of your plots in each stratum, during the baseline or initial sampling. The resulting data can indicate the variability among samples in a plot, and be used to gauge the sufficiency of your sampling design. During resampling, take multiple samples as before, but they can be bulked or composited by layer, thus saving lab costs.

Common conversions

starting with	multiply by	to get
acres	.405	hectares
hectares	2.47	acres
acres	4,047	square meters
hectares	10,000	square meters
tons of carbon	3.67	tons of carbon dioxide
tons of carbon dioxide	.273	tons of carbon
tons of carbon dioxide per acre	.11	tons of carbon per hectare
centimeters	.394	inches
inches	2.54	centimeters

Figure 3.1: Strong, sticky aggregation around perennial grass roots, caused most likely by abundant glomalin-forming mycorrhizae. USDA photo.

4

Sampling and field procedures

Once you have a basic design, assemble equipment and supplies, fill out the monitoring plan (page 38) and go take the samples. Sampling very dry soils or frozen soils is often difficult, and some soil moisture will make hand sampling easier. For consistency, it is a good idea to remonitor and resample at the same time of year as the initial baseline.

4.1 Lay out a transect and mark the plot center

One of the best ways to locate a permanent plot or microsite is by means of a **tape transect.** If possible, align the transect with permanent or long-lasting landmarks, and take a compass sighting as well as photographs and auxiliary measurements. During monitoring and sampling, the 200-foot or 50-meter tape will serve as a reference for all locations and sampling points.

The plot center should be at a certain point on the tape. Choose a plot center for a 4×4-meter plot where the plot area is relatively even and representative of a larger area. Pits, humps, or extensive rodent diggings at grid point 1 where you might take bulk density samples should be avoided.

At each end of the tape, permanent markers such as steel rebar stakes, bent in an upside-down J shape so as not to pose a hazard, can be set flush to the ground, perhaps through a piece of aluminum can for additional visibility. A white plastic bucket lid, though it may not last more than a few years in full sun, is also a visible marker and handy to stand on for consistent photos. Carefully record all locations, and take photos up and down the transect, using a small whiteboard or chalkboard as a label with date and project information.

I recommend marking the end points of the transect, rather than the plot center, which can be located by restretching the tape once the endpoints are located. The end points should be marked with something that will not interfere or pose a hazard to livestock, vehicles, agricultural equipment, etc. In pastures, an 18-inch section of $\frac{3}{8}$-inch rebar can be bent in a J or eye, perhaps with a couple of feet of aluminum wire affixed at one end for easier relocation, and driven flush. In cultivated fields a piece of steel such as rebar can be driven into the soil below the tillage layer, and subsequently located using a metal

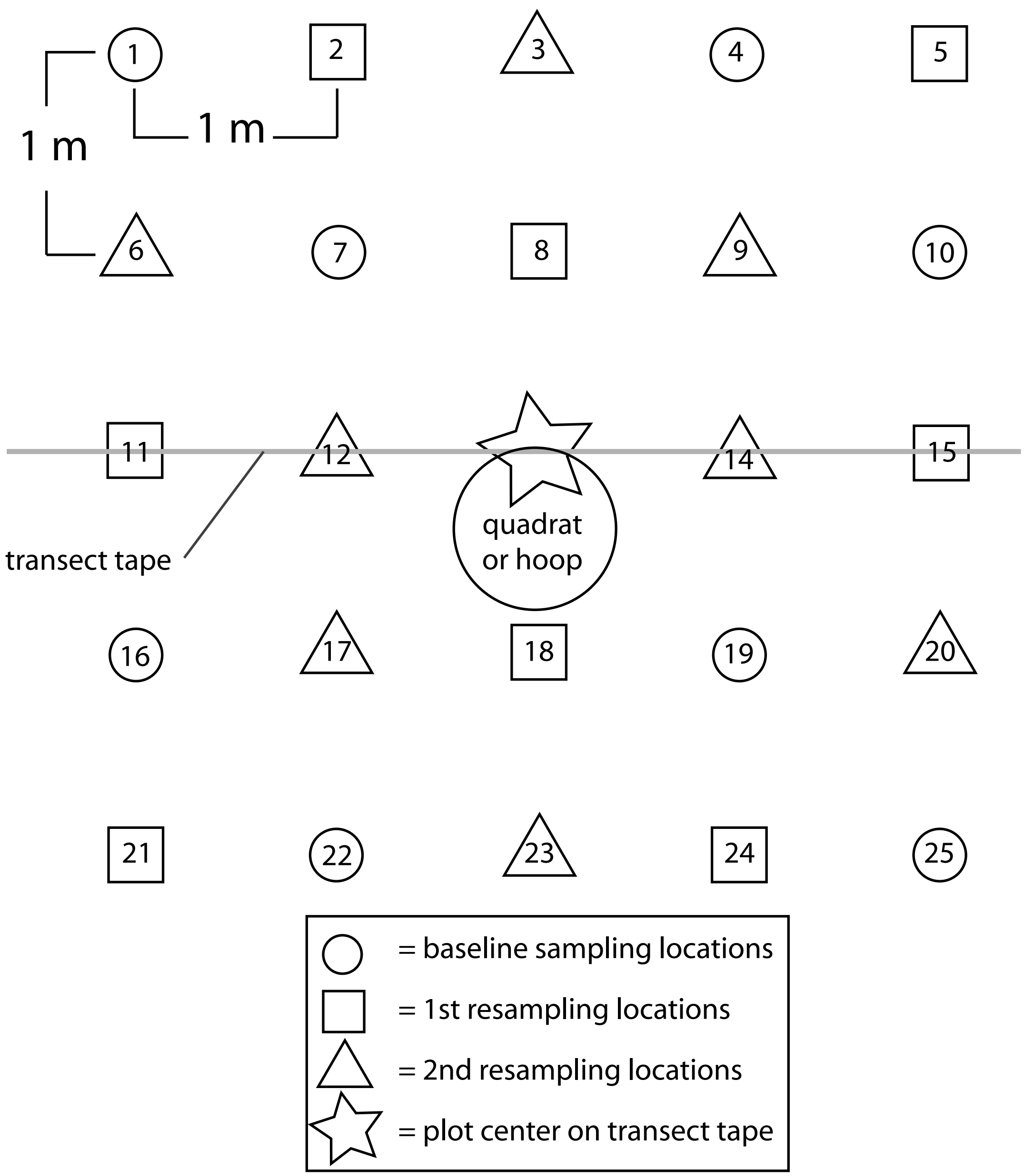


Figure 4.1: **A grid plot layout** provides 24 sampling locations, a meter apart, in a 4 × 4 meter square around the center point. At each sampling, up to 8 cores can be taken in previously unsampled points. Each core sample should be identified by its plot identifier as well as its numerical position on this grid, for example MF4-A21 indicating Muggy Farm, plot 4, position 21, layer A. For bulk density samples, use MF4-A21BD. If soil pits are needed, choose one of the outside locations. Use grid locations for bulk density sampling as well. After three samplings, the grid spacing can be expanded from 1 to 1.5 m to provide additional, previously unsampled points.

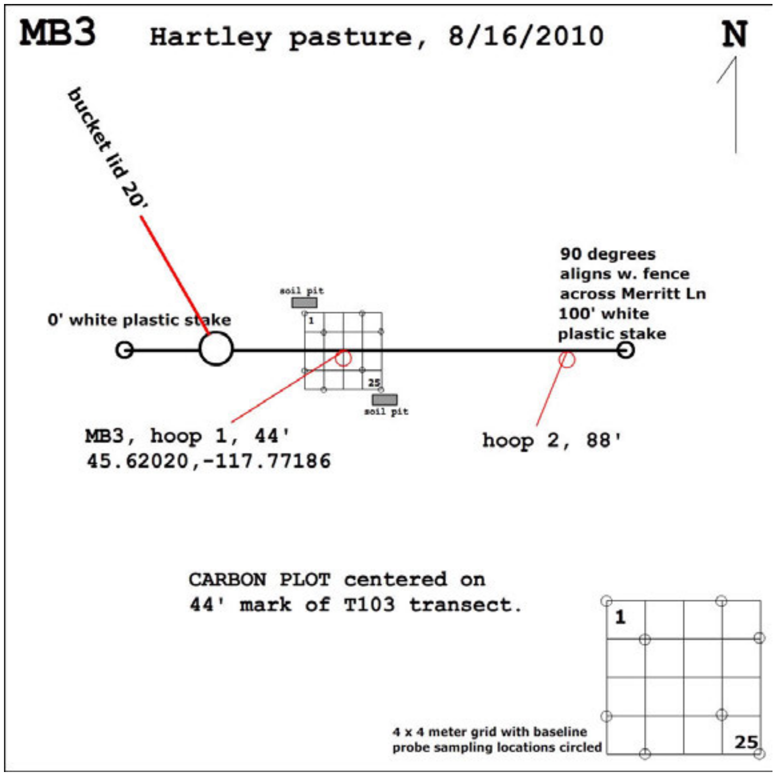


Figure 4.2: One of the best ways to locate a plot or microsite permanently is by means of a **transect**. If one or even two of your markers disappear, you can still relocate it. Draw a sketch map of each transect and plot as a guide for those who might remonitor the site. This will help you too. Note that this sketch map includes the 4 $\times$ 4-meter grid layout with the baseline sampling points indicated.

detector. In pasture lands, a plastic bucket lid fastened to the ground with pole barn nails may be a good marker, but not where wild pigs are common. I prefer three permanent markers.

A GPS receiver is a great idea in recording the photo point or ends of a transect, for general navigation and mapping, but don't rely on consumer-grade receivers to relocate your markers. Lines of sight and permanent markers, plus tape and compass, are superior.

Measured distances and compass bearings from fixed posts or landmarks can give additional means of relocating the plot. Plot locations can also be combined with soil surface monitoring locations.

Remember, if you can't find your transect or relocate it accurately, your work is wasted!

Do not mark plot centers with steel fence posts, as livestock or game may use the post as a rub, and potentially influence soil carbon change in the plot through their localized behavior and effects on the soil surface.

4.2 Soil surface observations

If your purpose with soil carbon measurement includes guiding management, this guide strongly recommends that you combine sampling for soil carbon with systematic monitoring of above-ground conditions. Land EKG is a good practical method for qualitatively and quantitatively assessing biosphere function in grasslands. Bullseye! monitoring is another. Either the Land EKG hoop or the Bullseye quadrat, plus related observations, should accompany soil carbon plots on rangeland.[4]

The 30-inch-diameter Land EKG hoop or should have its edge at the plot center (south edge in the southern hemisphere). A Bullseye quadrat can be located similarly. At the very least, take a photograph straight down onto the hoop or quadrat from approximately chest height while standing on the plot center. Include in the photograph the data sheet in this guide with the plot identifier, latitude and longitude, and date written large and clear.

As you observe changes in the conditions at the soil surface, for example better plant production and soil cover, so too you may observe an increase in soil carbon.

Look closely for signs of soil movement, erosion, or deposition. Wind or water moving soil across the landscape can be a significant cause of change in the amount of carbon measured over time. Plant pedestaling, litter dams, rills, or signs of sheet erosion all indicate soil loss. Tillage tends to erase signs of soil movement. Where soil is moving horizontally across landscapes, there is much less certainty about the causative processes of soil carbon change.

4.3 Lay out the plot

Stretch the tape. It is best to align the tape with landmarks if possible, for easier relocation. The very best is to align something near (say a church steeple or permanent power pole) with something far (such as the peak of a mountain).

With a sighting compass make sure cell phones or other magnetic influences are not nearby. Take a compass bearing along the tape. Choose a photo point (not necessarily the plot center) and take photos up and down the tape, making sure the tape bisects the photo, and include the foreground.

With a GPS receiver, get the coordinates of the photo point, preferably decimal degrees to five places. Write it down.

Use a meter stick to find grid locations relative to the plot center. Right angles can be trued by sight or by measuring 1.41 meters diagonally. For example, if your plot center is at 88 feet, set two meter sticks end-to-end at right angles from the 81.5-foot mark to locate one corner. Lay your meter sticks along the ground.

4.4 Use probe to take samples

After you have made soil surface observations, go after the core samples, trying to minimize disturbance of the soil surface while you do this.

The main thing to achieve here is taking a core sample that is representative of the layer you are sampling. If for example you are sampling to 40 cm, push your probe a bit more than 40 cm into the ground. Use a meter stick, or half a meter stick, to section your sample according to the layers you are sampling.

If there is crop residue, thatch, or partly decomposed litter, it is best to remove these gently from the soil surface with your fingers or a tool **before taking a probe sample.** Standard practice in soil carbon work is not to include the litter layer in soil carbon, but to begin sampling at the upper surface of mineral soil. Where sod is present, or litter is partially decomposed, this can be a difficult boundary to identify and create. Most laboratories will run samples through a 2-mm sieve, so pieces of litter in the sample can be ignored.

If your sampling location coincides with a woody plant of any size, do the best you can to get a soil sample at that location while minimizing damage to the plant, remembering that root fragments are generally sieved out during sample preparation, and can be discarded from the sample once they are clean of soil.

When taking samples below the surface, be sure that your core is uncontaminated by litter or by soil from other layers. Pile soil from digging or auger work onto a plastic or canvas sheet, and replace the soil when you are done.

Hand and foot operated probes work well in many situations. For loose and moist soil, thin-walled probes work best because they compact the least, and are least likely to clog and continue to penetrate, thus not taking a full core. In some clayey soils, a little water may help (but be sure the water does not contain significant amounts of dissolved solids such as calcium carbonate). Firmer soils will favor sturdier and thicker-walled probes, with slide hammer attachments often handy. Hydraulic probes are excellent for taking samples in hard dry ground, and for taking deeper samples. A probe with a diameter of an inch or somewhat less will give you a sample of adequate volume. Larger-diameter probes will retrieve larger samples, which you may want to divide lengthwise so as not to send pounds and pounds of soil to the lab for each sample.

4.5 Soils with abundant rocks, gravel, or coarse fragments

Small hand probes aren't effective in soils with lots of rocks or gravel. If it proves impossible to sample one or more layers fully because of rocks or gravel, you may choose to sample as best you can, note the depths of your samples, and move on. You may wish to add an extra plot or two if this occurs.

Rocks and coarse fragments may contain a significant portion of organic carbon in fissures and weathered pockets, and so pose an issue for measurement as well.

As grinding the rocks into powder for analysis is often impractical, the soil fraction consisting of particles larger than 2 mm is usually ignored.

In rocky or gravelly soils, it may be most practical to gather two samples each from four small soil pits, taking care to note the size and location of the pits relative to the plot center, so that future sampling can use different locations, and to restore the pits upon completion as fully and carefully as possible. To sample from a shovel pit, you should sample from the sides so that you know where the soil is from. For example, to sample 3 layers in a 40 cm pit, scribe the sides of the pit at the division points (e.g. 10 cm, 25 cm) and take samples from the side of the pit using a spoon.

4.6 Characterize the soil

For the plot, you may choose to describe all, some, or none of the following. These descriptions can give valuable context to your observations, but they may or may not be relevant to your purpose in monitoring soil carbon or biosphere function. These descriptions are all variable and subject to interpretation. Soil carbon is perhaps the best soil health and condition indicator, and it can be measured accurately via dry combustion/elemental analysis.

1. **Location notes.** Describe the location, and any correlations with soil surface monitoring transects or sites.

2. **Slope, aspect, and vegetation.** Approximate slope, and direction it is facing. If your sighting compass doubles as an inclinometer this is easy. Characterize the vegetation to the best of your ability.

3. **Moisture status.** Wet, dry, or moist. Use a moisture tester if you wish.

4. **Structure.** Is the soil granular, like sand, blocky, platy, prismatic, columnar, single grained, or massive?

5. **Consistency.** Is the soil loose, friable, firm, or extremely firm?

6. **Texture.** Approximate proportions of sand, silt, and clay.

7. **Rocks and roots.** None, few, many.

8. **Carbonates.** Carbonates such as calcium carbonate, $CaCO_3$ are inorganic. A few drops of distilled vinegar applied to soil (hydrochloric acid or HCl is the more serious approach) will effervesce if carbonates are present. Your ear rather than your eye may be a more sensitive detector of effervescence: put some soil in your palm (or in a ceramic dish if using hydrochloric acid), add a few drops to the soil, bring to your ear and listen closely.

9. **Aggregate stability** using the sieve test described in *Indicators of Rangeland Health*, Appendix 7, or `wiki.landscapetoolbox.org/doku.php/field_methods:soil_stability`

10. **Infiltration** such as a timed test using a tension infiltrometer.

For each core sample, **note the top and bottom depth in centimeters.** This is essential data. Characterize the litter-soil boundary, and note any differences from other samples in the plot.

4.7 Bag the sample

For samples to be analyzed singly, take the core from the top to bottom depth and place it in your sample bag.

Label each sample bag with a clear and unambiguous identifier with a permanent marker. The sample identifier should make reference to the land parcel, the plot, and the position of the sample with respect to the EZ-grid plot layout (page 21). For example, B6N3-A4 could refer to the Bar 6 Ranch, plot 3, soil layer A, grid position 4.

If you are combining several samples for analysis, a bucket or plastic container is handy for mixing or combining samples. Each sample or core should be evenly representative of the entire layer sampled, as soil carbon often decreases with depth.

Be sure to air-dry your samples as soon as possible after sampling to minimize oxidation of soil carbon.

4.8 Going deeper

It can often be difficult to push hand probes deep into the ground, starting from the soil surface, especially when soils are dry. Hammer-driven probes may be needed. It is sometimes necessary to excavate down to the next depth with the shovel or bucket auger, and start the probe from there, or obtain the sample in stages. Always be careful not to include soil or material from other layers. Some slotted probes will pick up soil along the bottom of the slot from other layers as they are pulled out, for example.

In rocky or otherwise difficult ground, hand-probe cores may be difficult or impossible to obtain. An alternative procedure is the **soil pit**, basically a hole in the ground with at least one vertical side which can be made with a shovel. Get your samples from the sides of the pit using a spoon, again taking care to make each sample representative of the entire layer sampled. If there are rocks or gravel present, do you best to collect a representative sample of fine earth from the top to the bottom of the layer.

4.9 Sampling for bulk density

Bulk density is the dry weight per unit volume of undisturbed soil. Measuring it requires taking a sample of known volume, drying it, and weighing it.

A simple and practical bulk density core sampler can be made out of a section of sturdy steel pipe about 3 inches or so in diameter. Exhaust pipe works well. Cut a section about 4 or 5 inches long, making sure the cuts are true and square. With a file or grinder, bevel the edge on one end from the outside of the pipe toward the inside at about a 45-degree angle. The inside edge should be square and reasonably sharp.

To take a bulk density sample, use a trowel or putty knife to prepare a flat plane surface of undisturbed soil near the midpoint of the layer you want to sample, at one of the grid locations. This can be a horizontal or vertical surface. With the block of wood and a hammer, tap the corer square into the flat surface of soil, at least 2 or 3 inches.

If the soil surface inside the ring moves inward as you tap, you are deforming the soil and may need to use the clod method described below.

The depth of the ring determines the soil volume contained. With a short metric steel rule, take four measurements, evenly spaced around the ring, of the distance between the outer or blunt edge of the ring to the soil surface within. The best steel rule to use is one with a movable slide or shirt-pocket clip, as you are often working in the bottom of a dark pit and can't read it accurately. The clip allows you to probe the depth from the rim of the sampler to the soil surface, and then remove the rule to read the distance in millimeters.

The average of these four measurements in centimeters, subtracted from the length of your corer, gives you the length of your bulk sample. Multiply this by the cross-sectional area of your corer (πr^2, where r is the inside radius of your corer) to get your volume. Using centimeters, your result will be in cubic centimeters, which simplifies the bulk density calculation. For example, my corer, made from a section of 3-inch steel pipe, has a cross-sectional area of 41.51 cm and a length of 11.0 cm. After I tap it into a flat surface of soil, it protrudes 5.65 cm (average of four measurements around the circle). The length of my sample is 5.35 cm $\times$ 41.51 = 222.0785 which I round to 222.1 cubic centimeters. **Write the volume in cubic centimeters, as well as the plot, grid position, and layer identifier, on your sample bag with a permanent marker.**

It is best to take these measurements **before** excavating your corer. In some situations you may want to seal the top of your corer with your sample bag and a rubber band so that no soil or other material leaves or enters the corer during excavation.

Now you are ready to excavate the corer. With the trowel or sharpened putty knife, carefully excavate the buried sharp end of the corer, so as not to interfere with the soil within it, until you can cut off the sample, flat and flush along the sharp edge of the corer (a serrated knife works well for this). Now you have a known cylindrical volume of undisturbed, uncompacted soil. Push it out of the corer and into your labeled sample bag, taking care to collect the entire sample. This may take a bit of practice.

The clod method

If you cannot take a sample using the this method because of gravel and rocks, or because the soil fractures or crumbles easily when the corer is tapped in, you may need to use the clod method.[5]

At one of the grid sampling locations, prepare a level plane surface of undisturbed soil at the needed depth, about midway down in the layer you are sampling. With the trowel, dig a bowl-shaped hole about 3 inches deep and 5 inches in diameter. Avoid compacting the soil around the hole while digging. Place all of the soil and gravel removed from the hole in a plastic bag.

Put the soil in the plastic bag through a 2-mm sieve and into a clean bucket. Put the sieved soil back into the plastic bag, and keep the gravel and rocks in the sieve. (If the soil is too wet to sieve, you'll need to save it for later, when you can air dry it, sieve it, and account for the volume of gravel by displacement in a graduated beaker or cylinder.)

Carefully line the hole with plastic wrap, leaving excess around the edge of the hole. Place the sieved rocks and gravel carefully in the center of the hole atop the plastic wrap, making sure they do not protrude above the level of the soil surface.

Using the 140-cc syringe to keep track of the volume, fill the hole with water up to the level of the soil surface. The volume of water required is the volume of the sample you have in the plastic bag. Write this volume in cubic centimeters on your sample bag.

Drying and weighing

Most soil labs will dry and weigh samples to calculate bulk density. You may also do this yourself, after the field sampling, if you have a gram scale accurate to .1 gram.

After the sample has been thoroughly air-dried, spread it on a microwaveable paper plate of known weight. (Large samples may require more than one paper plate.) Weigh the sample. Dry the sample thoroughly using a microwave at full power for 1–3 minutes depending on the size of the sample. If you smell smoke, you are overdoing it, combusting organic matter! Weigh the sample again, and record the weight. Microwave it again for 15 to 30 seconds. When it no longer loses weight after a short drying cycle in the microwave, it is dry. Record the weight of the dry sample in grams, less the weight of the paper plate of course. The bulk density D is

$$D = \frac{W}{V} \tag{4.1}$$

where W is the weight in grams and V is the volume in cubic centimeters (even including sieved-out rocks; see below).

It is important that the bulk density sample be as similar as possible to the carbon samples. If there are rock fragments larger than 2 mm in your bulk density sample, sieve out the rocks over 2mm in diameter and note the volume of the rocks using displacement with a graduated cylinder or beaker. However, and this is important, **do not subtract the**

volume of the sieved rocks over 2mm in diameter from your sample volume, but do not include them when weighing your oven-dried sample. In effect, this assumes that there is no carbon in these rocks, which may or may not be true, but unless you want to grind and analyze the rocks, you are better off just using the lower bulk density figure that results from not weighing the rocks in calculating the tons per hectare of carbon.

4.10 Resampling

It is common to wait three years or more between the baseline or initial sampling for soil carbon, and the first resampling. Weather can influence soil carbon accumulation or loss, and the longer you wait, the greater chance you have of detecting change due to management.

Resampling can follow most of the procedures outlined in this chapter, with two major exceptions:

1. To measure change, you will compare the mean carbon content for a plot at baseline with its mean carbon content on resampling, by layer of course. Thus it is not necessary to analyze samples within a plot separately, in order to assess within-plot variation. It is a good idea to take multiple cores as before, but they can be composited or bulked for analysis. For example, if you took 8 samples from the top layer during the baseline sample and analyzed them separately, you may now mix them thoroughly in a bucket and send off one or two subsamples of this mixture for analysis.

2. If the bulk density of a layer has changed more than a percentage point or two, you may need to engage in a bulk density correction.

4.11 Correcting for changes in bulk density

However, if the bulk density has changed more than a couple of percent, there is a wrinkle. We are now no longer comparing equal masses of soil.

Let's say the resampling, again to a depth of 15 cm, shows 2.0 percent carbon but with a bulk density of 1.15. Following the calculation below, we get 34.5 tons per hectare, a gain of only .525 tons per hectare per year. But because of the decrease in bulk density, we are sampling a lesser mass of soil than in the original sampling.

One strategy is to measure bulk density first on resampling, where possible. Compare it to the initial measurement, and then adjust sampling depths (and thus volume of soil sampled) so that you are sampling the same mass of soil. Use this equation to calculate the new volume that you should sample:

$$V_2 = \frac{V_1 \times D_1}{D_2} \tag{4.2}$$

where V_1 is the initial volume sampled, V_2 is the new volume to be sampled, and D_1 and D_2 are the first and second bulk densities measured. You can then divide the new volume by the area to get the new depth.

In cases where bulk density cannot be measured first, correction factors can be calculated for this eventuality.[6] Where bulk density has decreased, it involves sampling somewhat deeper, so that an equal mass of soil is compared, and adding the carbon in the additional depth.

Where bulk density increases, correction will involve resampling the bottom of the sampled layers and subtracting the carbon measured.

If bulk density changes, and you cannot adjust your depth of sampling, be sure to qualify your results by reporting it.

5

Getting your samples analyzed

In the U.S., many land-grant universities have soil and forage analysis labs that perform the dry combustion test using CN (carbon-nitrogen) or CNS (carbon-nitrogen-sulfur) analyzers, such as those made by Leco, Perkins-Elmer, Elementar, or Carlo-Erba. Many of these labs also do some sample preparation such as drying, sieving, and grinding.

Private soil labs are less likely to do elemental analysis, because it is more of a research analysis than a guide to chemical application.

5.1 Sample preparation

Air dry your samples as soon as possible. Just as plowing and tilling soil exposes soil organic matter to rapid oxidation by common bacteria, taking a sample of moist soil and keeping it in a sealed bag will result in oxidation. One common method is to spread each sample on a paper or plastic plate or piece of clean paper, with the labeled plastic bag underneath or stapled to the plate or paper, and when it is dry, return the sample to the labeled bag for shipping to a lab.

Laboratories vary in their sample preparation procedures, which can have significant impacts on the reported results. The drying, sieving, and grinding aren't all the same. Some labs may not sieve samples, thus including significant root fragments or litter, which are likely to boost carbon content.

A common standard is to air-dry soil samples, crush them or grind them enough to pass through a 2-mm sieve to remove gravel and root fragments, and then pulverize the sample in a grinder or mortar and pestle. Some researchers or labs may remove visible plant and root fragments by hand after sieving, but others do not.

One option is to do the sample preparation yourself. This will require a mortar and pestle (Coorstek 750ml porcelain mortars are often used) and a 2-mm sieve. After breaking up the clods in the sample so that they can be sieved, spread the sieved sample on a sheet of paper and collect a **carefully representative subsample** for fine pulverization in the mortar. This subsample is then subsampled for the elemental analyzer. So careful homogenization and subsampling is critical to accurate measurements.

For detecting change, the most important thing is **consistency between measurements.**

5.2 Storing samples

In measuring change, you don't get any data until your resampling is analyzed. It is possible to store your dried, bagged baseline samples in a cool, dark, dry place, and only send them for analysis along with the samples from the resampling. This strategy has the advantage that the sample preparation and analysis at the lab is likely to be more consistent when the work is done at one time, rather than with a gap of three or more years.

5.3 Split sampling to test your lab

Mix a core sample very thoroughly in a bucket. With alternating spoonfuls, bag it as two or more samples, labeled separately. Keep a record that this is a split sample.

1. Send both samples to the same lab, and compare the results. This is one way to sample a lab's work.
2. Send each sample to a different lab.
3. Have one sample tested, and store its twin in a refrigerator or cool, dark, dry place for a year, which should not change the carbon content provided that the sample is thoroughly dried before storage. Then send it to the same lab that tested the first sample.

5.4 U.S. labs that do elemental analysis or dry combustion test

Use the internet to get more information. It is a good idea to call to get an idea of what their testing procedures are, and sample preparation. Some labs, for example, will routinely try to separate organic and inorganic carbon for you, especially if the pH is above 7 or an acid test indicates the presence of carbonates, and are unaccustomed to running total carbon tests on all samples.

Most labs accept samples by mail or package service.

institution	**web address**
Oklahoma State	`www.soiltesting.okstate.edu`
Utah State	`www.usual.usu.edu`
Oregon State	`cropandsoil.oregonstate.edu/cal`
University of Idaho	`www.agls.uidaho.edu/asl/`

6

Data

> Our results suggest that grassland soil C changes can be precisely quantified using current technology [soil sampling and dry combustion] at scales ranging from farms to the entire nation.
>
> Rich Conant and Keith Paustian, "Spatial variability of soil organic carbon in grasslands" (2002)

What you do with your data depends on your purpose, why you are measuring soil carbon change.

If you are only interested in quantifying the tons of carbon added, may want only the mean or average. This is a drastic simplification of the data. While it may appear to be precise, and to tell a simple story, much is being left out. Averages leave out lots of relevant detail: the average human has approximately one ovary and one testicle. Keep all your raw data. You may want it later.

6.1 Carbon calculations

After you have gotten analysis results from your lab, you may make some basic calculations. But it is only after resampling that you will have any idea of change in soil carbon.

To calculate mass of carbon in a single stratum (layer of soil in a horizontal stratum), it takes three factors. Use this formula:

$$C_T = C_F \times D \times V \tag{6.1}$$

where C_T is total carbon for the layer in metric tons, C_F is the fraction of carbon (percentage carbon divided by 100), D is density, and V is volume of the soil layer in cubic meters.

For example, let's say our plots in this stratum average 1.8 percent carbon, our bulk density is 1.20, and we're sampling to a depth of 15 cm on a 12-hectare field. Since there are 10,000 square meters in a hectare, our volume is 120,000 $\times$ .15 m, or 18,000 cubic meters. So our total carbon for the layer is .018 $\times$ 1.2 $\times$ 18,000 = 388.8 tons, 32.4 tons per hectare.

If we resample this field after four years and our plots average 2.0 percent carbon, and the bulk density is still 1.20, we now have 432 tons C or 36 tons to the hectare, an average gain of 3.6 tons per hectare, or .9 ton C per hectare per year.

A shortcut equation giving tons of carbon per hectare is:

$$T = Th_{cm} \times D \times C_{percent} \tag{6.2}$$

where T is tons of carbon per hectare, Th_{cm} is the thickness of the sampled layer in centimeters, D is density, and $C_{percent}$ is the percentage of carbon. If testing several layers, add the tonnage in each layer to get a total tonnage for the layers sampled.

You can then qualify your results with confidence intervals and standard error if you wish (see statistics chapter) and/or get some qualified help with statistical processing.

6.2 Replicability

These three factors—volume of the layer sampled, bulk density, and percentage of total carbon—are critical for a replicable, consistent measurement. There are two additional factors as well.

1. The volume of the layer sampled means you must be accurate in measuring and sectioning soil probe cores, and get an even representation of the layer in each core. Do not just scoop up a sample of soil from somewhere close to the depth desired.

2. Good bulk density measurements are needed. The bigger the better, and two are better than one.

3. Sample drying, subsampling, and elemental analysis (dry combustion) should be accurate and consistent.

4. Permanent location of sample grid sites is critical. Consumer-grade GPS receivers are helpful but not sufficient to locate transects markers. If you, or someone else, can't find the plot or microsite, the measurement is not replicable or repeatable. Multiple permanent stakes or markers, use of metal detectors to find steel stakes, and measurement and triangulation to permanent landmarks, and the mapping of each site are needed for replicability.

5. Open yet secure data. If you are using proprietary or secret methods, or if you don't publish raw data with clear indications of how the data was obtained, your measurement is not replicable.

6.3 Greenhouse gas emissions

Many people are justifiably concerned about the totality of greenhouse gas emissions from agriculture and ranching. They may ask, so what if you're sequestering carbon in the soil. What about all the methane that your livestock are producing? Or the nitrous oxide? Or what other kinds of carbon dioxide emissions are you causing?

Greenhouse gases—so called because though they are transparent, they absorb radiation in a variety of wavelengths, and re-emit a portion of it as heat—include water vapor (the principal greenhouse gas), carbon dioxide or CO_2, methane or CH_4, and nitrous oxide or N_2O.

If you wish to account for your emissions of some of these other gases, there is a rudimentary calculator in Excel format, targeted to grass-based cattle producers, at `soilcarboncoalition.org/calculator1`

However, it can be difficult or expensive to quantify rather than model emissions in your particular case, and water vapor is not included in the calculator. Likewise the rate of methane oxidation by soil bacteria is not typically measured.

6.4 Data entry and mapping

Many labs will offer to email data from multiple samples to you in a spreadsheet form such as Microsoft Excel. This can save you a lot of data entry if you have many plots. Some labs can begin with a spreadsheet that you submit, that could contain your plot and sample identifiers as well as dates and GPS coordinates where the sample was taken.

To display your data on Google Earth or Google Maps, you need a .kml file, which is a text file in the Keyhole Markup Language format. There are a number of software tools that can help you convert spreadsheet files into .kml and display data as points with information balloons on Google Earth or Maps. Google Fusion Tables are a handy way to map multiple data points. See also `zonums.com` for a free spreadsheet-to-kml tool.

Data interpretations may vary and change. So it is a good idea to keep raw data, and any information that might show how it was arrived at.

6.5 The Soil Carbon Challenge

> Merely measuring something has an uncanny tendency to improve it.
>
> Paul Graham

You may also submit your results to the Soil Carbon Coalition, a nonprofit organization dedicated to advancing the practice, and spreading awareness of the opportunity, of turning atmospheric carbon into soil organic matter. The Soil Carbon Coalition can present your data and display your results on a Google map.

See `soilcarboncoalition.org/changemap.htm` for the map, which shows measured instances of soil carbon change in the same location.

Where monitoring is facilitated and led by a trained third party monitor, in accordance with this guide, the Soil Carbon Coalition will accept entries for the Soil Carbon Challenge, a public, international, yet localized competition to see how fast and how well land managers can turn atmospheric carbon into water-holding, fertility-enhancing soil organic matter.

The purpose of the Soil Carbon Challenge is to enable us to learn how to better manage the carbon cycle, which greatly influences water cycling on land. It is not designed as a "fix" for climate change, but to enable learning on the part of both land managers and larger society based on results and measurements, rather than on various kinds of advocacy or solutioneering.

If we measure, pay attention to, and publicly recognize the conversion of atmospheric carbon dioxide into soil carbon, it will assist a fundamental transformation—to managing *for* what we want and need (soil organic matter) instead of *against* what we don't want (e.g. fossil fuel emissions).

Because of this purpose the Challenge does not often use a high number of plots for each property—in some cases only one—a biased selection—usually chosen to be fairly representative of a major portion of the property being managed.

See `soilcarboncoalition.org/challenge` for current information.

7

Forms and checklist

Following are some forms and a checklist that should tell you at a glance what is involved in measuring soil carbon change, and help keep you on track through the process.

7.1 Basic equipment

item	**description**
sharpshooter shovel	a long narrow-bladed shovel
soil probe (smaller diameter)	for extracting soil cores
hammer probe	for sampling more difficult soils
bulk density corer	short section of 3-inch pipe, outside beveled on one end
hammer, wood block	for tapping in bulk density corer
140 cc syringe, plastic wrap	for measuring clod volume
6-inch steel rule, metric	for measuring bulk density cores
2-mm sieve	for sample prep and bulk density clod method
plastic or canvas sheets	for piling dirt from holes
plastic containers	for collecting and mixing samples
serrated knife and sharpened putty knife	for cutting soil
sharp pointing trowel	for shaping and excavation
sample bags	quart ziplocs work well
permanent markers	for labeling sample bags
camera	for photographing plots
GPS receiver	for mapping plots
sighting compass/inclinometer	for laying out plots
meter sticks	for measuring cores and laying out plots
200-foot or 50-meter tape	for laying out plots and fixing location
clipboard and data forms	for recording data

7.2 Monitoring plan

Name of parcel:	acres/hectares:	sampling #:
Purpose. Why?		
Other monitoring:		

major soil types/zones	approx. size or %	number of plots

TOTAL PLOTS:____________

FIRST SOIL LAYER	top (cm):______	bottom (cm):______
samples per plot:______	number of analyses:______	
SECOND SOIL LAYER	top (cm):______	bottom (cm):______
samples per plot:______	number of analyses:______	
THIRD SOIL LAYER	top (cm):______	bottom (cm):______
samples per plot:______	number of analyses:______	

add analyses for layers to get Total carbon analyses per plot:______

multiply by number of plots to get **TOTAL carbon analyses:**____________

Number of bulk density tests per plot

first layer: ______ second layer: ______ third layer:____________ TOTAL: ______

multiply by number of plots to get **TOTAL bulk density tests:**______

Unit costs quoted by soil lab:____________________________________

C analysis: _________ bulk density: _________ sample prep: _________

TOTAL ESTIMATED LAB COSTS:________________________

7.3 Monitoring checklist

1. Map your site, with boundaries and possible horizontal strata. Google Earth is a good tool for this, but a paper map works too. (*baseline only*)

2. Fill out the monitoring plan on page 38. Depending on your purpose, use sampling calculators (page 49) to help you decide on the number of plots for each stratum, and the number of samples per plot, and where in the grid they will be.

3. Collect any necessary equipment and supplies, including those needed for any additional monitoring. Where underground utilities are a possibility, call before you dig.

4. Choose plot sites, using your maps and monitoring plan as a guide. Give each one a unique identifier. (*baseline only*)

5. At each plot, record its location with GPS, compass, and tape measure. Draw a map of the plot area (*baseline only*)

6. Do any observations and data collection for soil surface monitoring. Photograph the plot center hoop from chest height, labeled with plot identifier, latitude and longitude, and date writ large on side 1 of the plot data form.

7. Take bulk density samples and bag them, writing the volume in cubic centimeters clearly on each bag.

8. Record bulk density samples, optional soil info on plot data form.

9. Lay out the sample locations you will need using tape and meter sticks, and take sample cores. Use the grid diagram on page 21 for layout and sample locations.

10. Replace soil that you have excavated, pick up your tools.

11. Spread your samples on plastic picnic plates, with sample bags labeled and stapled to them, to air dry.

12. Pack your air-dried samples in a box and send them to your lab.

13. If you are doing your own bulk density tests, do them and record results.

14. Record and process data when you get results back from the lab.

7.4 Plot data form

The following two pages can become a two-sided form for recording data. On one side, write the plot identifier, latitude and longitude (decimal degrees is best if you plan to work with Google Earth or .kml files), and date. Write large, in permanent marker, and photograph this form with the soil surface. Use the other side to record plot and sample data.

Because of the common failure of digital cameras to record black text on white paper in bright sunlight, it is best to copy these data forms onto grey or tinted paper (or card stock).

When you get lab results, you can enter these, and then enter the data into a spreadsheet for analysis and mapping. But hang onto your plot data forms, even after you enter the data in a spreadsheet or web application. They are the most secure form for data, and the raw data is often much richer and more informative than the statistical interpretations such as mean and standard error.

plot data sheet for soil carbon, side 1: write large, and photograph this sheet with soil surface

plot identifier

latitude

longitude

date

Plot data sheet for soil carbon, side 2

Plot ID: Stratum:	Project: Your name:

location notes	
slope, aspect, vegetation	
moisture	rocks and roots
structure	carbonates
consistency	aggregate stability
texture	infiltration

sample ID	lab results	top	bottom	litter-soil boundary, comments

8

Signal vs. noise (statistics)

> It is far better to have an approximate answer to the right question than an exact answer to the wrong one.
>
> John Tukey

Because of variations in soil carbon and rates of change from place to place, and because we can't and shouldn't combustion test all soil for carbon content, estimating soil carbon accurately (or change in soil carbon) is a sampling problem involving statistical probabilities. This chapter may give you some understanding and background for the statistical issues that a sampling design should take into account. The first section below is the basics, and then comes the harder math, which you can get help with from others.

Use what you want. As mentioned previously (page 7), the sources of uncertainty depend on your purpose. Statistical uncertainty, while it may be quantified more easily than other kinds, may not be the major source of uncertainty or risk in achieving your purpose or objective with soil carbon measurement. If your purpose is feedback to management or to find out what's possible in improving soil carbon at a few strategic locations, statistical knowledge may not be helpful.

8.1 Sampling and probability

Three tax returns, randomly chosen, are unlikely to give you an accurate view of the average personal income in a town, its spread, or its rate of change. So too with soil sampling. According to widely accepted statistical theory and practice, the confidence that the mean or average of your samples is close to the overall mean of what you are sampling increases in proportion to the square root of the number of samples.

With 16 samples you will be twice as confident as with 4. The probability that the average of your samples is a fluke decreases by half. With 64 samples you will be 4 times as confident.

The other factor that affects confidence is variability. The more variable the percentage or change in soil carbon, for example, the more samples you will need to reduce the probability that the mean of your samples differs significantly from the mean of what you are sampling.

Each sample takes time and labor to obtain, and money to have it analyzed. Thus there is a tradeoff between high levels of confidence or statistical power on the one hand, and trouble and expense on the other. Where you draw this line depends on your purpose in sampling.

When we are **measuring change** in soil carbon, the sample or data point is the change or difference in the carbon content at a single plot over a time span. Some of the statistical discussions in the current literature about measuring soil carbon can be confusing because they are oriented around measuring carbon at one point in time.

Variability, and the number of samples or data points, are the factors that govern statistical accuracy and confidence. When measuring change, one of the best ways to detect a signal over the "noise" of spatial variation is to measure carbon content in a small area (the plot) over time. The closer you can get to comparing apples to apples, the easier and more accurate the measurements.

8.2 Standard error

Perhaps the most widely used description of the margin of error in sampling is the standard error or sampling error (SE), often described as the standard error of the mean, or the standard deviation of all possible sample means of the given sample size:

$$SE = \frac{\sigma}{\sqrt{n}} \tag{8.1}$$

where σ is the standard deviation of all the possible soil cores in the layer (for which s, the standard deviation of the sample, is the best estimate) and n is the number of soil cores. For example, suppose I take 8 core samples in a plot, have them analyzed separately for carbon, with the following results.

sample ID	carbon percentage
MF3-1	1.2
MF3-4	1.3
MF3-7	2.1
MF3-10	2.4
MF3-16	1.8
MF3-19	1.6
MF3-22	1.5
MF3-25	2.3
mean	1.775
s	.4528

using the above formula, the standard error is $\frac{.4528}{\sqrt{8}}$ or .16. The more samples you take, the smaller the standard error or sampling error.

8.3 Coefficient of variation

In statistics, a standard measure of variability is the coefficient of variation (CV). This is the ratio of the standard deviation (σ) to the mean (μ). It is sometimes expressed as a percentage.

$$CV = \frac{\sigma}{\mu} \tag{8.2}$$

The calculators referenced on page 49 will give you an idea of the number of samples you need for a given confidence level, given the coefficient of variation. Note that the required sample size does not depend on the area of land sampled, but on the variation.

However, for measuring soil carbon change, our sample datum is not the concentration or mass of carbon in a given volume of soil, but the **change** in that concentration or mass. What this means is that you cannot know the coefficient of variation in advance of the second sampling, because that is when you get your first data on change. If your sampling intensity is less than you want, you cannot go back and correct it.

Presampling, taking a few samples and having them analyzed before finalizing a sampling design and intensity, may give you an idea of the coefficient of variation for soil concentrations, but will not necessarily give you a grip on the variability of soil carbon change.

Therefore, the resolution or confidence of the results from your sampling design cannot be predicted in advance. You must establish plots or benchmarks with a reasonable number of samples within each plot, and accept whatever variability occurs in change over time, along with the level of confidence that it allows.

In many areas of study where statistics are used, anything less than 95% confidence ($p \leq .05$) is not considered “statistically significant.” But this is an arbitrary standard, and many soil studies use a more relaxed 90% or $p \leq .1$. Statistical significance depends on your purpose. Are you seeking feedback for your land management, trying to show a possibility, trying to sell something, or are you trying prove something beyond all reasonable doubt to a jury of your peers?

8.4 Comparing paired samples

If you understand some statistics, use the paired sample t-test to qualify your results. Here three examples.

Bar 6 Ranch, north half

plot	T_0	T_1	Δ
1	36.2	38.6	2.4
2	32.0	34.2	2.2
3	26.9	28.0	1.1
4	41.3	42.0	0.7
5	39.1	39.8	0.7
6	40.1	42.5	2.4
7	37.6	37.5	-0.1
8	29.0	31.1	2.1
9	31.4	33.1	1.7
10	30.9	31.4	0.5
11	42.3	44.9	2.6
12	18.1	18.3	0.2
mean	33.74	35.12	1.375
s	7.01	7.42	0.964

where T_0 is the calculated average tons of carbon per hectare for each plot to a 15 cm depth at the baseline in 2005, T_1 is the same from resampling in 2009, Δ is the change, and s is the standard deviation across the plots. The estimate we're after is that of change. For the paired sample test, use this formula:

$$\mu_d = \bar{d} \pm t_{.025} \left(\frac{s_d}{\sqrt{n}} \right) \tag{8.3}$$

where μ_d is the probable range of the mean change in carbon, $\bar{d}$ is the mean change across plots, $t_{.025}$ is the critical value of t for a 95% confidence interval and 11 degrees of freedom (in this case 2.2), s_d is the standard deviation of the change across all plots, and n is the number of plots. Plugging in the numbers, we get μ_d = 1.375 $\pm$ .613, or a probable increase in carbon ranging from .762 to 1.988 tons per hectare.

Here's an example with fewer plots and more variability:

Muggy Farm

plot	T_0	T_1	Δ
1	54.6	61.2	6.6
2	65.8	68.2	2.4
3	45.2	44.1	-1.1
4	65.7	66.1	0.4
5	39.5	45.8	6.3
6	40.1	42.5	2.4
7	57.1	63.2	6.1
8	32.1	32.3	0.2
mean	50.02	52.9	2.912
s	12.65	13.33	3.06

Plugging in the numbers here, again with a 95% confidence interval, and t at 2.3646 with 7 degrees of freedom, we get 2.912 $\pm$ 2.558, or a probable increase of .354 to 5.47 tons of carbon per hectare in the layer sampled. Though this farm had over twice the average increase of the ranch, there were fewer plots, and more variation in the changes, giving considerably less resolution of the change. (The coefficient of variation for the changes on the ranch is 70% versus 105% for the farm.)

With the 95% confidence interval, on Muggy Farm we can assert that there has been at least a .354 ton increase. If we relax the confidence interval to 90% (a 10% probability that our estimate misses the actual value), we get 2.912 tons per hectare $\pm$ 2.0494, or .8626 tons to 4.96 tons, a slightly narrower range.

8.5 Stratified sampling

Chances are, the soil to be sampled varies both by depth and by horizontal location. With soil, we can set up zones or strata that are both vertical (depth) and horizontal (for example, different management, vegetation, slope, soil type).

If you are trying to estimate personal income or change in income in a town, you can gain resolution and possibly reduce the needed number of samples by sampling neighborhoods separately that are likely to differ. You may choose to sample the wealthy, middle class, and poorer neighborhoods separately, which may reduce the variability encountered, tightening your overall estimate. The means of these samples can then be combined on a weighted basis to give an estimate for the whole town.

Suppose that a farm consists of 754 acres of farmed ground and 246 acres of pasture (1,000 acres total). Because the pasture was not tilled, highly productive, and well managed, we expect soil carbon to increase significantly faster there than in the farm ground. We put in 7 plots on the farm ground and 5 on the pasture (not a proportional representation), and found these results after 4 years (figures in tons per hectare).

754 farmed acres			
plot	T_0	T_1	Δ
1	36.2	36.4	0.2
2	34.3	35.2	0.9
3	28.6	29.8	1.2
4	29.7	30.8	1.1
5	31.2	32.2	1.0
6	33.1	33.9	0.8
7	37.8	38.9	1.1
		mean	.90
		s	.337
246 acres pasture			
8	34.5	37.4	2.9
9	39.0	41.8	2.8
10	24.3	27.5	3.2
11	21.9	23.7	1.8
12	27.9	30.2	2.3
		mean	2.60
		s	.552
		nonweighted mean	1.609
		nonweighted s	.969

Using the formula as above, the overall mean result is an increase of 1.609 tons, $\pm$ .616 tons, or a range from .99 to 2.22 tons, with a 95% confidence interval. This calculation assumes (unfairly) that each plot has equal weight on the end result. The spread is fairly high.

However, if we treat the farm ground and the pasture as two separate areas, we get a different picture. For the farm ground alone, we get a mean of .9 tons $\pm$ .311 tons, or .59 to 1.21 tons. For the pasture alone, we get 2.6 tons $\pm$ .686 or 1.91 to 3.29 tons.

These can be combined into a weighted mean as follows:

$$\bar{x}_w = \frac{\sum_{i=0}^{n} w_i x_i}{\sum_{i=0}^{n} w_i} \tag{8.4}$$

where $\bar{x}_w$ is the weighted mean, n is the number of plots, and w_i is weight factor for each plot. This routine gives each plot a weight factor in proportion to the acreage it represents and divides by the total of the weight factors. The weighted mean change across our plots is 1.318 tons.

To get the standard error is a bit trickier. Using the formula from the National Institute of Standards and Technology, the weighted standard deviation sd_w is:

$$sd_w = \sqrt{\frac{\sum_{i=0}^{n} w_i(x_i - \bar{x}_w)^2}{\frac{(n-1)\sum_{i=0}^{n} w_i}{n}}} \tag{8.5}$$

where n is the number of plots, w_i is the weight assigned to each plot, x_i is the mean change for each plot, and $\bar{x}_w$ is the weighted mean change across all plots. A spreadsheet makes these calculations easier.

If we combine the plot differences on a weighted basis, according to acreage of each stratum, we get 1.318 tons ± .543, or .776 to 1.86 tons per hectare. Because the levels of change in the farmed ground and the pasture differ, we gain resolution by treating the strata separately. Our weighted estimate is both different from, and tighter than, the unstratified overall estimate.

8.6 Help with statistics

There are many statistical analysis software packages. The spreadsheet program Microsoft Excel has a Data Analysis Toolpak that is free to install (choose Tools, Add-Ins from the menu), and can do many basic statistical tests such as the paired sample t-test for comparing plot means between samplings.

Because the statistical significance of a collection of samples depends on the number of samples rather than on the area of the field or farm that you are sampling, sampling intensity (the number of samples) should go up if you expect a high degree of variability, and/or you need high resolution or accuracy.

The Microsoft Excel worksheets available from the USDA-ARS can be helpful in getting a feel for sampling intensity, and its relation to variability:

`usda-ars.nmsu.edu/monit_assess/`

Appendix 2 of USDA's *Soil Change Guide* has information and instructions for this Multi-Scale Sampling Requirements Evaluation Tool (MSSRET). The MSSRET tool asks for *rho* which is Pearson's correlation, the degree of correlation between a plot's before and after readings. For paired plot sampling, it is reasonable to set *rho* fairly high, such as .9 or above.

`soils.usda.gov/technical/soil_change/`

In addition, Winrock International has a sampling calculator that presupposes bulked samples for each plot, and allows you to plan stratifications.

`www.winrock.org/ecosystems/tools.asp`

While these worksheets are not specifically targeted at measuring differences over time between fixed plots, they are helpful in calculating the number of plots, and the number of samples per plot, needed for a given confidence interval, minimum detectable difference (MDD), and ranges of variation.

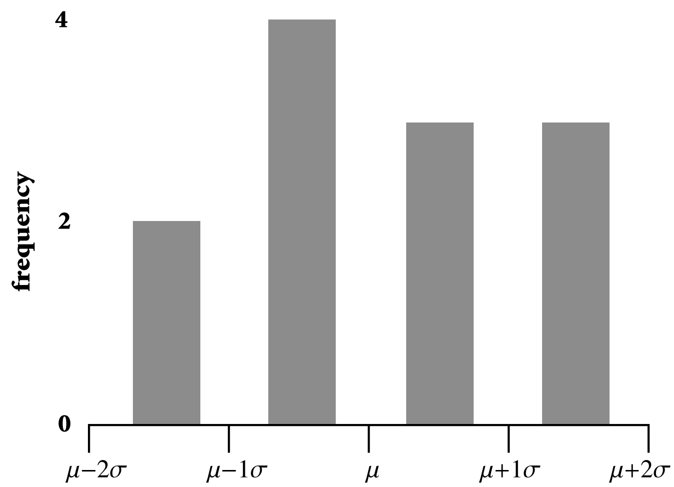


Figure 8.1: A histogram or frequency chart of the soil carbon change data from page 46. The number of plots recording change at levels one or two standard deviations above and below the mean are represented by the bars. Note that this representation reduces and simplifies the data.

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The use of statistical analysis or complicated math and formulas does not guarantee accuracy. If your plots are not located randomly, much of statistical theory and analysis does not apply. Where you locate plots may have more influence on the accuracy of your results than the variability of soil carbon change, about which relatively little is known or quantified. And in many cases, where your objective goes beyond mere enumeration of tons of carbon, statistical uncertainty may be overshadowed by other sources of uncertainty or risk.

Much of conventional or parametric statistics requires or assumes that the measurable characteristics of populations are normally distributed, especially when n, the number of samples, is below 30 or so. For example, the heights of adult humans, if charted as a histogram or frequency chart, will closely resemble the bell curve or normal distribution, with a hump around the mean.

But because there has been relatively little measurement of soil carbon change, we really don't know what typical distributions or parameters might be. Particularly when the number of samples is low, nonparametric statistical tests, such as the Wilcoxon rank sum test, may be more appropriate than t-tests.

As usual, it comes down to purpose. If your purpose is to demonstrate possibility or create a desired future, a high degree of statistical accuracy or confidence may not be your top priority.

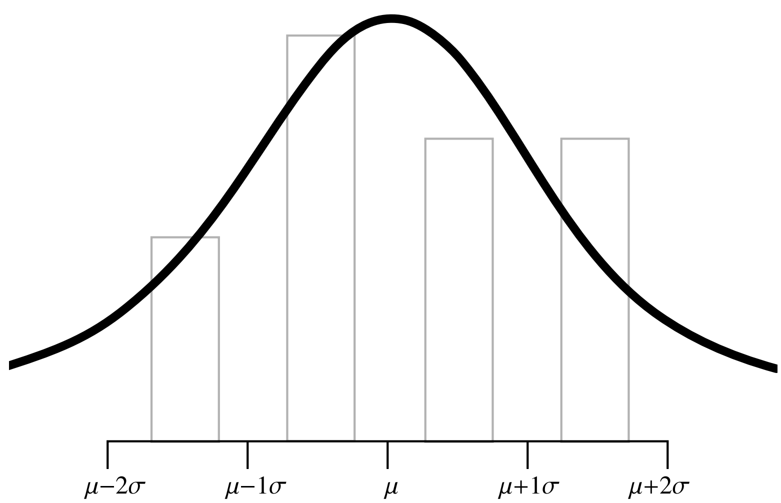

Figure 8.2: An even further reduction of the data from page 46 sees it as indicating a normal or bell-curve distribution, which may not be a warranted assumption given the relatively small sample size.

9

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Notes

[1]Annual Net Primary Production (NPP) for the United States, average of years 2000 through 2006, is about 3.273338 petagrams or gigatons (billion metric tons) of carbon (Maosheng Zhao, personal communication, October 2007). For data on terrestrial net primary production see Zhao, M., F. A. Heinsch, R. R. Nemani, and S. W. Running, Improvements of the MODIS terrestrial gross and net primary production global data set, *Remote Sensing of Environment* 95: 164–176 (2005).

Since 1 g of NPP carbon represents 3.9×10^4 joules (PowerPoint at http://tinyurl.com/35fagm), the net primary production of the United States represents an energy capture of 1.276×10^{20} joules or 128 exajoules. (Sven Jorgensen in his *Towards a Thermodynamic Theory for Ecological Systems*, Elsevier 2004, uses the figure 4.2×10^4 joules per gram.) By contrast, U.S. use of all types of industrial, transport, and thermal power in 2006, minus about 3% of biomass energy, was 96.3 quadrillion BTUs (Energy Information Administration, November 2007 monthly review, accessible from http://www.eia.doe.gov/emeu/aer/overview.html). Multiplied by the conversion factor of 1,055, this converts to 1.02×10^{20} joules or 102 exajoules. So current photosynthesis, in the United States, is about 25% more than energy use that is not tied to current photosynthesis.

Worldwide, annual NPP is probably about 110 Gt C, counting the oceans. World energy use for 2004 was estimated at 447 quadrillion BTUs (http://www.eia.doe.gov/oiaf/ieo/world.html). Converting both figures to joules as previously, world NPP comes to 42.9×10^{20} joules or 4,290 exajoules, whereas energy use is 4.71×10^{20} joules or 471 exajoules. Worldwide, net current photosynthesis represents about 9 times as much as other human energy consumption.

[2]Allan Savory's book *Holistic management: A new framework for decision making* (Island Press, 1998) is the classic text on the holistic management framework, and includes a description of the plan-monitor-control-replan sequence. In his book *The new economics* (MIT Press, 1994), W. Edwards Deming explains the plan-do-study-act cycle that he adopted from Walter Shewhart.

[3]Deming made an important distinction between enumerative and analytic studies (Chapter 7 in *Some Theory of Sampling* from 1950). An example of an enumerative study is the U.S. Census, to determine representation in the House of Representatives. Another is sampling a shipload of iron ore to estimate a likely price, and the risks of paying too much or selling for too little. An analytic study, on the other hand, aims at identifying and influencing the causes of change, such as identifying practices or management for enhancing soil carbon. Deming wrote, "Techniques and methods of inference that are applicable to enumerative studies lead to faulty design and faulty inference for analytic problems" ("On probability as a basis for action," from 1975). *The New Economics* (1993) also treats the subject briefly on page 100.

[4]For Land EKG, see `landekg.com`. For Bullseye, published by the Quivira Coalition, see `http://quiviracoalition.org`

[5]This clod method is taken from the USDA Soil quality test kit guide, prepared by John Doran.

[6]For more detailed explanations about calculating carbon when bulk density changes, see pages 137–38 in Rattan Lal's volume, *Assessment methods for soil carbon* (2001), and Appendix 16 in Willey and Chameides 2007.

Index