Terrestrial Carbon Sequestration

Analysis of Terrestrial Carbon Sequestration at Three Contaminated Sites Remediated and Revitalized with Soil Amendments

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Version 1, www.cluin.org/ecotools

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Introduction

Thousands of acres of Superfund, Brownfields, and mining sites, landfills, and industrial sites with contaminated or disturbed soils exhibit a variety of problems that often can be addressed effectively and directly through the application of soil amendments (EPA, 2007). Soil amendments are generally residuals from other processes that have beneficial properties when added to soil. Commonly used amendments include municipal biosolids, animal manures and litters, sugar beet lime, wood ash, log yard waste, neutralizing lime products, composted biosolids, composted food scraps and yard trimmings, and a variety of composted agricultural byproducts. Applied properly, soil amendments reduce exposure to contaminants at these sites by limiting many of the exposure pathways and immobilizing contaminants to reduce their bioavailability. The addition of amendments also restores soil quality by balancing pH, adding organic matter, increasing water holding capacity, re-establishing microbial communities, and reducing soil compaction. The use of soil amendments enables remediation, revegetation, reuse, and ecological revitalization of contaminated properties.

Along with achieving the U.S. Environmental Protection Agency (EPA)'s goal of site remediation and reuse, there are many co-benefits gained from ecological land revitalization. These benefits are known as ecosystem services. Ecosystem services are the direct or indirect benefits that ecosystems provide to the well-being of human populations (EPA SAB Report "Valuing the Protection of Ecological Systems and Services, May 2009). Ecosystem services include terrestrial carbon sequestration and storage, climate regulation, clean water storage and filtration, natural recreation areas, wildlife habitat, species diversity, pollination, flood and erosion control, food production, fiber, cultural practices, scenic landscapes, soil formation, nutrient cycling, aesthetics, and more. These goods and services have traditionally been viewed as public goods or "free" benefits, such that their critical contribution is often overlooked in land-use decision-making. However, these services are increasingly viewed as having economic value; therefore, markets that provide payments for ecosystem services are being considered and developed. Early examples of ecosystem service markets are regulation-driven wetland mitigation and carbon credit trading to offset carbon dioxide (CO_2) emissions.

This paper presents the results of a study of the terrestrial carbon sequestration co-benefit of using soil amendments for remediation and ecological revitalization at three sites. Terrestrial carbon sequestration is the process through which CO_2 from the atmosphere is absorbed by trees and plants through photosynthesis and stored as carbon in soils and biomass (tree trunks, branches, foliage, and roots; www.epa.gov/sequestration/faq). Another benefit associated with soil amendment application is that it can prevent CO_2 and methane (CH_4) emissions into the air that would otherwise be associated with the disposal of industrial by-products (i.e., biosolids and other soil amendments). Carbon-rich soil amendments are applied to remediate contaminated sites, a practice which reuses materials that can emit greenhouse gases when disposed, adds a high concentration of carbon to carbon-devoid land, and provides an environment for plant growth. In addition to carbon storage in soils, vegetative growth of trees and plants on the site pulls CO_2 from the air (as part of the photosynthesis process) and cycles it back into the soil. Therefore, soil amendment application provides both a one-time carbon benefit (load) at the time of application and an annual carbon sequestration benefit (rate) in the new functioning ecosystem until the carbon reaches equilibrium. There are also carbon reduction benefits in using an organic source of nutrients and avoiding the CO_2 emissions associated with producing synthetic fertilizer.

To date, little research has been published evaluating and quantifying terrestrial carbon sequestration benefits associated with contaminated lands remediated with soil amendments (i.e., Superfund sites, Brownfield sites, etc.) (Brown, 2009 Personal Communication; Tian et al, 2009; Shukla et al, 2005). There are a number of references in the scientific literature that address soil carbon sequestration rates for revitalized mine, agricultural, and forested lands showing a large potential for terrestrial carbon sequestration if these lands are managed correctly (Tian, et. al. 2009, Trlica, 2010). Some Superfund and other contaminated sites devoid of vegetation contain very little soil organic carbon, providing a great potential for building soil organic matter and sequestering carbon. Also, ecosystems would likely not develop on contaminated sites without external inputs.

To increase knowledge regarding terrestrial carbon sequestration, EPA collected and analyzed samples at three field sites to quantify soil carbon sequestration rates. As part of this study, EPA developed a methodology for field sampling and analysis of carbon in soils at amended sites. This protocol was developed so that EPA and other researchers can use a consistent approach for collecting samples so that data can be compared across a range of sites. This protocol, entitled "Terrestrial Carbon Sequestration: Field Guide for Sampling and Analysis for Sites Remediated with Soil Amendments" and located at www.cluin.org/ecotools, is a living document that will be updated as more is learned about terrestrial carbon sequestration and improved data collection and analytical methods. The methodology described in the protocol was field tested at three different sites across the country and the results are presented in this paper.

This paper provides EPA's analysis of the data to determine carbon sequestration rates at three diverse sites that differ in geography/location, weather, soil properties, type of contamination, and age. The first site, located at high elevation in Leadville, Colorado, suffered from contamination due to mining. The site was amended with biosolid cakes, biosolids pellets, biosolid compost, and limestone starting in 1998. The second site, located in Stafford County, Virginia, had highly reduced, high-sulfur soils resulting from construction activities for an airport at the site. When exposed to air, these soils rapidly acidified, causing acid runoff that contaminated local streams. The site was amended with biosolids in 2002. The third site, Sharon Steel, is located at the border of Pennsylvania and Ohio and was contaminated through the application of by-products associated with manufacturing steel (an adjacent steel plant operated for almost 100 years). At Sharon Steel, soil amendments were applied as part of a field demonstration project in 2008.

The preliminary results of work performed as part of this study, indicate that carbon is being sequestered at all three sites. To grow knowledge in this area, future field work and literature reviews are required. Additional useful information would include a database of carbon sequestration ranges that could be used to estimate terrestrial carbon sequestration rates based on soil type, soil amendment type and application rate, geographical information, and weather/climate data.

EPA shares information on terrestrial carbon sequestration on its EcoTools webpage (www.cluin.org/ecotools). Future work planned in this area includes: public presentations; internet trainings; scoping exercises for determining carbon balance, additionality, and permanence of terrestrial carbon sequestration at sites; additional site analysis; and collaboration with others interested in this topic.

Background

The carbon cycle is comprised of all living things (humans, animals, vegetation). Carbon (C) continuously circulates between five major interconnected reservoirs: the atmosphere, oceans, geological sources, biota, and the terrestrial biosphere. The oceanic pool contains the most carbon with 38,000 Petagrams (Pg), followed by the geologic pool (fossil fuels) with 5,000 Pg (one Pg is equal to 10^{15} grams). The geologic pool contains approximately 4000 Pg of carbon as coal, 500 Pg of carbon in oil, and 500 Pg of carbon in natural gases. The terrestrial pool is the third largest with 2300 Pg of carbon: 1,550 Pg of Soil Organic Carbon (SOC) and 750 Pg of Soil Inorganic Carbon (SIC). The next largest pool is the atmospheric pool containing 760 Pg, and lastly, the biotic pool with 600 Pg of live mass and detritus material. Compared to both living vegetation and the atmosphere, the world's soils store considerably more carbon. Therefore, even relatively small changes in amounts of soil carbon can have a significant impact on the global carbon balance (Rice, Charles W. 2002).

Carbon is present in the nonliving environment as carbon dioxide (CO_2) gas in the atmosphere, as dissolved carbon in water (forming bicarbonate and carbonate solutions), and in carbonate rocks, coal, petroleum, natural gas, and dead organic matter (humus). Carbon is found in the atmosphere primarily as CO_2, CH_4, and chlorofluorocarbons (CFC). Table 1 provides characteristics of some major carbon-based and other gases that contribute to global warming. Carbon enters the biotic world through the action of autotrophs, which are organisms capable of synthesizing their own food from inorganic substances using light or chemical energy. Photoautotrophs, like vegetation and algae, use the energy of the sun to sequester CO_2 from the atmosphere and convert it into organic matter such as sugars and carbohydrates.

Table 1. Characteristics of Gases Contributing to Global Warming[1]

Characteristic	CO_2	CH_4	N_2O
Atmospheric concentrations	ppm	ppb	ppb
Preindustrial	280	700	270
Current	370	1745	314
Atmospheric lifetime (years)	5-200	12	114
Per molecule ratio of radiative forcing[2] (CO_2 equivalent)	1	23	296

Notes: CO_2 = carbon dioxide; CH_4 = methane; N_20 = nitrous oxide; ppm = parts per million; ppb = parts per billion.

1 Source: Brown, S. and P. Leonard, "Biosolids and Global Warming: Evaluating the Management Impacts," *Biocycle*, August 2004.

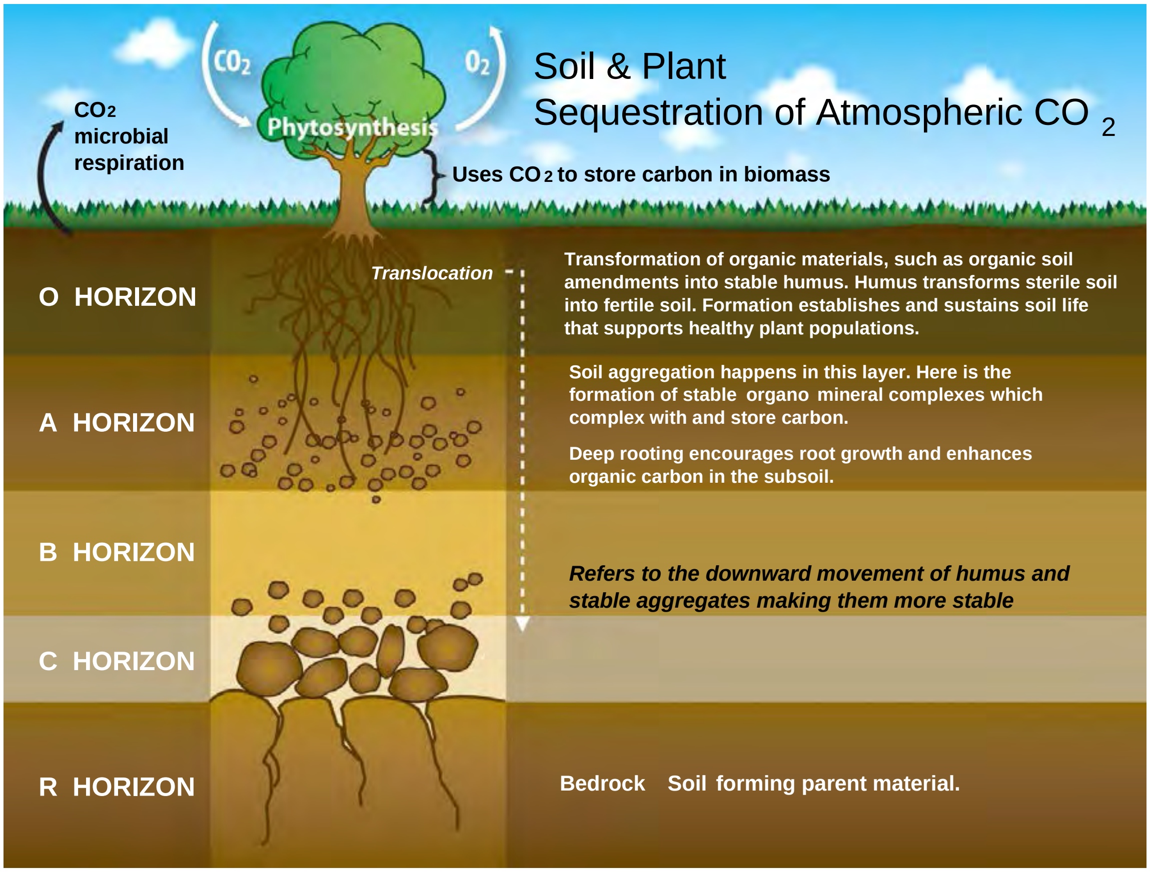
2 "Radiative forcing" refers to the differential trapping of heat in the lower atmosphere by gas molecules. High positive radiative forcing values in the lower atmosphere versus the upper atmosphere tend to warm the earth's surface (IPCC 2007). Radiative forcing produced by different greenhouse gases is measured relative to CO_2.

Carbon sequestration also occurs in soil supporting plant growth. Plants convert CO_2 into tissue through photosynthesis, which leads to translocation of carbon through plant roots into the soil. As plant material decomposes, primarily by soil microorganisms, much of the carbon in the plant material is released through respiration back to the atmosphere as CO_2. However, a portion of the carbon is stored in organic matter, creating organic residues, called humus. These carbon-rich residues can persist in soils for hundreds to thousands of years. Factors influencing carbon storage in soils include climate, temperature, rainfall, clay content, and mineralogy.

Carbon in soils is present in a range of forms. The average residence time for carbon in soils is 10 to 30 years. Different types of carbon compounds will have different rates of decay. Some compounds like humic acids can persist for hundreds to thousands of years. Other compounds including simple carbohydrates may only persist for days or months. Recent research has indicated that carbon in soil aggregates is more resistant to decomposition than carbon that is not associated with minerals. A new type of carbon, glomalin, has also been identified as an important factor in forming these aggregates. It is also important to understand that high carbon soils support high productivity plants. This means that plants growing on high carbon soils tend to have more biomass than plants growing on low productivity soils. As plants with greater biomass decay, more biomass is returned to the soil carbon pool, further increasing soil productivity and carbon storage. The two discrete pools in which soil carbon is stored are (1) the short term biomass that is easily decomposed, in which carbon may reside for as little as a few weeks, and (2) the pool in which carbon is more tightly held by physical encapsulation within soil aggregates or chemical complexes, where it may reside for tens of thousands of years. Natural carbon sequestration processes through which vegetation extracts atmospheric CO_2 through photosynthesis to build biomass is shown in Figure 1. Some of the biomass is converted into stable humic substances, some of the carbon bonds with clay to form stable complexes, and some is respired back into the environment.

Soil scientists began studying soil systems in relation to greenhouse gases in the early 1990s. An initial focus of study was intensified agriculture, which began around 1860 and released large amounts of carbon from the soil. These agricultural releases compounded other releases of carbon to the atmosphere from the intensive use of fossil fuels during the industrial age. From the early 1900s to the 1990s there has been an estimated loss of 40% of soil carbon from the central U.S. Corn Belt in the top 20 centimeters (cm) of soil. These large carbon losses from agricultural soils have been reversed due to large-scale adoption of reduced till or no till practices (Lal et al, 1999), which have turned soils from a carbon source to a carbon sink. Carbon sequestration in soils associated with the adoption of no till practices based on U.S. data has been estimated at 0.42 ± 0.46 Megagram (Mg) carbon per hectare per year (Mg C/ha/year), or 0.62 ± 0.68 Mg CO_2/acre/year (Franzluebbers, 2005), and at 0.308 ± 0.280 Mg C/ha/year, or 0.46 ± 0.42 Mg CO_2/ha/year (Spargo et al., 2008). An estimate based on global data is 0.48 ± 0.13 Mg C/ha/year, or 0.71 ± 0.19 Mg CO_2/acre/year (West and Post 2002). In comparison, CO_2 uptake in northern latitude forests (accruing to both biomass and soil) has been estimated at 2.0 ± 0.2 Mg C/ha/year, or 3 ± 0.3 Mg CO_2/ha/year (Barford et al. 2001).

Figure 1. Soil & Plant Sequestration of Atmospheric Carbon Dioxide



Notes: CO_2 = carbon dioxide. O_2 = oxygen.

Studies have also demonstrated that more carbon is sequestered in soils where biosolids are applied in addition to implementing no till or reduced till strategies. In an agricultural study of the Virginia coastal plain, Spargo et al. (2008) found that no till sites that had previously received biosolids sequestered 4.19 ± 1.93 Mg C/ha more over the 0-15 cm soil depth interval than no till sites that had not. Other studies have demonstrated the beneficial effects of biosolids applied for reclamation of mined lands. Tian et al. (2009) reported carbon sequestration rates ranging from 0.54 to 3.05 Mg C/ha/year over a 34 year reclamation period involving multiple applications of biosolids to strip-mined land in Fulton County, Illinois. These rates were net sequestration values that documented soil carbon gains after accounting for residual biosolids. Such studies that have highlighted the carbon sequestration benefits of biosolids in agricultural and mine reclamation settings provided precedents for EPA's pilot study to further document the potential benefits of soil amendments across a broader range of restored and remediated sites.

Background on Study Sites

For this study, three sites were identified to evaluate the potential for soil carbon sequestration on contaminated land where soil amendments were used for remediation and revitalization. The sites were selected based on their location, dates of amendments application, and willingness of site stakeholders to participate in the study. The three sites include: (1) a mining site in Leadville, CO,

(2) an airport in Stafford County, VA, and (3) an industrial by-product disposal site in Mercer County, PA, named Sharon Steel. Table 2 provides a summary of the sites.

Leadville

The Leadville site is the California Gulch Superfund site, operable unit 11, located approximately 100 miles southwest of Denver, CO, in Lake County. Figure 2 includes photographs of the site. Silver, gold, lead, and zinc were mined and milled in Leadville for 120 years. The sulfide rich mine tailings washed down into the Arkansas River impacting an 11 mile stretch of the river. The tailings caused acidic conditions and metal contamination that made the area inhospitable for vegetative growth. The site was listed on the National Priority List (NPL) in 1983.

The soil type is sandy loam and the site elevation ranges from 8,200 to 10,000 feet above mean sea level. The weather is typical of mountainous areas and ranges from 86°F in summer to -30°F in winter. The wind is predominately from the northwest and ranges from calm to 30 miles per hour (mph). Average annual precipitation is 11.6 inches. Precipitation occurs sporadically, causing occasional flash floods. The precipitation and temperature cycles give rise to peak runoffs in the spring, usually during June. Annual snowfall depths from mountains in the area range between 200 inches (”) and 300” with 6” of snow cover commonly found in the town of Leadville during the winter months.

The site was remediated from 1997 to 2003 using various types of biosolids amendments including biosolids, compost, biosolid pellets, wood chips, agricultural limestone, and cow manure. The site was revegetated with a variety of grasses, sedges, and clovers, and is currently functioning as a restored natural and agricultural (grazing) habitat.

More information on the California Gulch Superfund Site is available at:

- www.epa.gov/region8/superfund/co/calgulch
- www.epa.gov/superfund/sites/rods/fulltext/r0805045.pdf
- www.brownfieldstsc.org/pdfs/CaliforniaGulchCaseStudy_2-05.pdf

Stafford

Stafford County is approximately 35 miles south of Washington, DC. Construction began in December of 1997 for a private 550-acre airport with 15 acres of paved aircraft parking space, and a 5,000 foot by 100 foot runway. The airport was completed in December 2001. During airport development, seven million cubic yards of earth was moved and this exposed and distributed underlying sulfide bearing sediment (pH < 3.5). The result was exposure of acidic soil with some run-off to a nearby stream. Photographs of the site are shown in Figure 3.

The site is characterized by rolling hills and sandy loam soil. Based on data for the years 1895 to 1998, the maximum average temperature occurs in July (86.1°F) and the average low temperature occurs in January (26°F). The average annual precipitation totals 43 inches. During the month of September, anywhere from 10 to 40 percent of Virginia’s total annual rainfall comes from hurricanes and tropical storms (http://climate.virginia.edu/description.htm, accessed January 2010).

Table 2. Overview of Sites for Terrestrial Carbon Sequestration Study

Type of Site	Amendment Type	Amendment Period and Rate of Application	Study Sampling Date	Weather Mean Annual Temperature and Precipitation[1]	Elevation	Soil Type	Acres
Leadville Superfund Site – Leadville, Lake County, CO							
Former mine tailings site (Superfund)	Biosolids, compost, pellets, limestone, wood chips, manure	1998-2001; 100 dry tons of biosolids per acre, 100 dry tons of lime per acre	Fall 2008	Temperature: 35°F Precipitation: 12 in.	9,928 ft	Sandy Loam	80[2]
Stafford Airport Site - Stafford, VA							
New development/ construction (airport)	Biosolids, straw mulch, salt tolerant grasses	2002; 120 dry tons per acre	Fall 2008	Temperature: 56°F Precipitation: 43 in.	106 ft	Sandy Loam	257.5[3]
Sharon Steel Farrel Works Disposal Area (Sharon Steel) Superfund Site – Mercer County, PA							
Redeveloped steel mill (Superfund)	Biosolids, compost, and pine bark	2008; field pilot demonstration – application to 6 in. depth over pilot plots	Fall 2008	Temperature: 49°F Precipitation: 43 in.	1,194 ft	Silty Loam	400[4]

Notes: F = Fahrenheit; ft = feet; in = inches; mm = millimeter.

1 Source: www.usclimatedata.com. Accessed August 2010.
2 Superfund site is approximately 11,500 acres; 80 acres were amended.
3 Approximately 257.5 acres were amended; the sampling area was 1.2 acres, but is representative of the site as a whole.
4 Superfund site is approximately 400 acres. It has not been determined how many acres will be amended.

Figure 2. Leadville Superfund Site, Lake County, CO. The picture on the top was taken in 1996 prior to remediation with soil amendments. The picture on the bottom was taken in 2008 during sampling for terrestrial carbon sequestration. Photographs courtesy of Harry Compton and Michele Mahoney, EPA.

In the fall of 2002, lime stabilized biosolids from several nearby municipalities were applied to the site (Orndorff et al., 2008). Treatments were designed to neutralize the potential acidity of the soil and provide nutrients needed to establish vegetation. The biosolids were applied by side slingers, allowed to sit for a couple of days, then disked, and finally planted with salt tolerant grasses. The grasses consisted of Kenblue Kentucky bluegrass, redtop, annual ryegrass, and tall fescue.

More information on the Stafford Airport site is available at: www.cses.vt.edu/revegetation/remediation.html .

Sharon Steel

The Sharon Steel Farrell Works Disposal Site (Sharon Steel) site occupies approximately 400 acres and is located southwest of the city of Farrell, Mercer County, PA, near the Pennsylvania-Ohio border. The site is southwest of the former Sharon Steel Corporation Farrell Works, and is bordered on the east by the Shenango River. The Sharon Steel Corporation was founded in 1900 to manufacture a variety of steel products and steel manufacture operations continued until 1992 when Sharon Steel declared bankruptcy. Beginning about 1900, the Sharon Steel Corporation used the area to dispose of blast furnace slag, electric arc furnace slag, basic oxygen furnace slag, and sludge. From 1949 to 1981, millions of gallons of spent pickle liquor acid were dumped over the slag. It was thought that the acid would partially evaporate and then be neutralized by the carbonates in the slag. In actuality, groundwater contamination resulted. Contamination in soil consists of metals, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and pesticides. The site is located in the flood plain of the Shenango River, and includes several wetland areas. An aerial photograph of the site is shown in Figure 4. The site was listed on the NPL (Superfund) in 1998.

The western bank of the Shenango River is located on the site; the topography consists of hilly uplands and broad deep valleys cut by the river. The soil generally consists of silty loam. Normal temperatures for this site range from 9°F to 75°F. Annual precipitation for 2008 totaled 37.8 inches with the wettest months being June and July and the driest months being January and September. Average annual precipitation is 43 inches. Snowfall in 2008 exceeded 208 inches, with heavy snows experienced in December (http://climate.met.psu.edu/www_prod, accessed January 2010).

In 2006, a laboratory treatability test was performed to determine if the application of biosolids could reduce mobility of metal contamination, reduce the bioavailability of metals in the slag/sludge, and restore the soil to allow for vegetative growth. Results were promising and in 2007 a pilot-scale field study was performed to further evaluate the effectiveness of applying biosolids. The 2007 plots were not able to produce vegetation likely due to high pH and lack of precipitation that year. In 2008, a new pilot study area was established. The 2008 pilot study area was sampled to evaluate carbon sequestration for this study. Various application rates of the biosolids were also evaluated in this pilot study. The plots were vegetated with a fast-growing cover crop in conjunction with a native seed mix.

Figure 4. Sharon Steel Farrell Works Superfund Site, PA. Photograph courtesy of Rashmi Mathur, EPA.

More information on the Sharon Steel Farrell Works Superfund Site is available at:

- www.epa.gov/reg3hscd/npl/PAD001933175.htm
- www.epa.gov/reg3hscd/super/sites/PAD001933175
- www.clu-in.org/ecotools/images/03_EcoRevInfoSession_Case_Study_2.jpg

Sampling and Analytical Results

Sampling and analysis was performed using an EPA methodology developed specifically for field sampling and analysis of carbon in soils at amended sites. This protocol, "Terrestrial Carbon Sequestration: Field Guide for Sampling and Analysis for Sites Remediated with Soil Amendments," was developed to support consistency across sites and can be found at www.cluin.org/ecotools.

This section provides the analytical results for soil samples that were collected to evaluate carbon sequestration associated with soil amendment application. Table 3 summarizes the measured carbon sequestration rates for the three sites, calculated in megagrams (Mg, equivalent to metric tons) of carbon per hectare (ha), Mg CO_2 per ha, and Mg CO_2 per acre. The calculations of sequestered carbon applied bulk density (BD), percent carbon (%C), and other data reported from the soil sampling and analysis program, as follows:

$$\%C \times BD \times AD \times \frac{10{,}000\ m^2}{ha} = Mg\ C\ per\ ha$$

Where: % C = Mean percent carbon content of amended soil over the depth interval and treatment unit of interest

BD = Mean bulk density (in Mg/m3)

AD = Amended soil depth interval of interest (in m)

m = meters

Mg = megagrams (equal to metric tons)

ha = hectare

Conversions of these results to CO_2 equivalents in Mg (metric tons) per hectare and Mg per acre are as follows:

$$\frac{Mg\ C}{ha} \times \frac{44\ g/mole\ CO_2}{12\ g/mole\ C} = \frac{Mg\ CO_2}{ha}$$

$$\frac{Mg\ CO_2}{ha} \times \frac{1\ ha}{2.47\ acres} = \frac{Mg\ CO_2}{acre}$$

Carbon results are generally reported in metric tons of CO_2 equivalents and compared to reference sample data to determine the carbon sequestration potential at the amended area. This potential is referred to as the carbon sequestration "additionality" of a treated area over an untreated area. A "sequestration rate" over time is also presented by dividing the Mg CO_2 per acre value by the number of years since the application of soil amendments to report Mg CO_2 per acre year. These calculations are further discussed in EPA's Field Study Protocol (www.clu-in.org/ecotools). Following the calculation summary for the three pilot sites in Table 3 is a detailed description of the results by site.

In addition to soil sampling and analysis, EPA collaborated with C-LOCK® Technology, Inc., to model the carbon sequestration rates at the sites. The C-LOCK® System is a computer model driven methodology for determining a site's annual differential carbon storage given natural occurrences and human-induced changes to the site. The methodology uses a Monte Carlo-based uncertainty analysis in conjunction with real site weather and GIS-derived soil information. Adaptation of the C-LOCK® System from agricultural lands to remediation sites is an evolving process. The modeling results from Leadville were inconclusive. The modeled C-Lock value (1.7 metric tons CO_2/acre year) for the Stafford site was within the same magnitude of the actual measured values. C-Lock modeling predicts a carbon sequestration rate of 1.3 metric tons CO_2/acre year for Sharon Steel.

Table 3. Study Carbon Sequestration Results Summary[1]

Site (Location)	Soil Type	Amendments	Metric tons (Mg) C/ha [2]	Metric tons CO_2 / ha	Metric tons CO_2/ acre	Metric tons CO_2/acre/ year
Leadville (CO)	Sandy Loam	Biosolids, compost, pellets, limestone, wood chips, manure	52 - 86	190 – 315	78 - 127	10.2 [3]
Stafford (VA)	Sandy Loam	Biosolids, Straw Mulch, salt tolerant grasses	10	36	15	2.5
Sharon Steel (PA)	Silty Loam	Biosolids, compost, and pine bark	0 - 45	0 - 165	0 - 67	NA[4]

Notes: CO_2 = carbon dioxide. C = carbon. Mg = megagram. ha = hectare. NA = not applicable.

1 Results are presented for the surface soil sampling interval (0-15 centimeter soil depth). The results represent "net" carbon sequestration values calculated by subtracting mean carbon content values of reference areas from those of the treated areas; see results discussion below. Results are presented in a range of units that are commonly used in carbon sequestration studies.

2 Ranges of carbon sequestration rates are presented below for the multiple types of amendment applications that were deployed at the Leadville and Sharon Steel sites. For the Stafford site, only a single type of amendment application was used.

3 Estimate is based on net mean carbon sequestration values calculated for the amended areas; see results summary discussion below.

4 Sharon Steel is a demonstration site and the soil amendments were applied right before sampling; therefore, the carbon numbers are for a one time application, and only with additional time can a yearly sequestration rate be calculated.

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Leadville

At the Leadville site, many different soil amendment scenarios were evaluated in the 1990s to establish the best method for remediation and revitalization of the site. For this study project, five different treatment and reference areas (designated LP, LB, LC, LU, and LR) were selected for soil sampling to determine the rate of carbon sequestration in the soil.

Sampling was performed by Lockheed Martin, Inc., of Edison, New Jersey, a contractor to the EPA Environmental Response Team. Three sampling grids of 40 feet by 40 feet were defined at each of the five treatment areas. Three random soil sample points were selected in each sampling grid by randomizing a Cartesian (x,y) coordinate system established in the grid. Samples were collected from two depths at each sampling point, 0- 15 cm and 15- 30 cm. The sampling depths were selected based on the characteristics of degraded lands that have been restored; these only have a minimal depth of healthy soil, given that it takes hundreds of years to create an inch of soil. While it is likely that a restored ecosystem function will, in time, increase soil carbon below a depth of 30 cm, that increase is unlikely to be measureable within the timeframe of this study.

A composite sample was collected from each sampling point by placing a quartered square sampling template on the ground. One subsample was taken from each quarter and put into a bucket. Once all of the subsamples from each quarter were in the bucket, the soil was mixed into a composite sample and then put into sample jars for submittal to the laboratory. Sample analysis was performed by the National Health and Environmental Effects Laboratory (NHEEL) of EPA's Office of Research and Development (ORD) in Corvallis, Oregon. Samples were analyzed in triplicate for pH, Electrical Conductivity (EC), %C, %N, and bulk density in the fall of 2008.

Sampling occurred September 23 to 25, 2008. On September 23, the mean temperature was 40.1°F (4.5°C) with a maximum temperature of 53.6°F (12°C) and a minimum temperature 28.4ºF (-2°C), with no precipitation. On this date the mean wind speed was 4.95 mph, with a mean dew point of 24.2°F (-4.33°C). On September 24, the mean temperature was 40.1°F with a maximum temperature of 53.6°F and a minimum temperature of 28.4°F, with no precipitation. On this date the mean wind speed was 4.95 mph, with a mean dew point of 24.2°F. On September 25, the mean temperature was 46.2°F (7.89°C), with a maximum temperature of 64.9°F (18.28°C) and a minimum temperature of 27F, with no precipitation. On this date the mean wind speed was 4.37 mph, with a mean dew point of 18.4°F (-7.56°C). There was a variety of grass and fescue at all sample locations except LU.

Table 4 summarizes sampling results for pH, EC, %C, %N, bulk density, and C:N ratio at each sampled treatment area, as well as the Mg (equivalent to metric tons) of carbon (C) per hectare (ha), and the metric tons of CO_2 per acre. The summarized results are the mean results for the three soil sampling points collected at each of the five areas. (Each sample was analyzed by the laboratory in triplicate giving a total of nine results for each analytical parameter and sampled area.) In addition to the soil samples summarized in Table 4, biomass samples (roots and shoots) were also collected in each sampling grid. The sampling results for each treatment area are further discussed below. The results are discussed for the 0-15 cm soil depth, unless otherwise noted.

LP

Area LP was amended in 1999 with 100 dry tons/acre of biosolid pellets and 100 tons/acre of limestone. In the three 40 by 40 ft grids sampled in 2008, the mean soil bulk density was 1.5 g/cm^3, EC was 2.5, and pH was 5.9. The EC and bulk density values are above typical soil optimum ranges (Table 4). The biomass samples showed an average of 1,428 kg/ha in the shoots and 1,883 kg/ha in the roots. Area LP was subject to animal grazing. Table 4 shows that among all of the Leadville treatment areas, LP had the largest amount of Mg C/ha for both the 0 – 15 cm depth and the 15 – 30 cm depth; LP stored 218 metric tons CO_2/acre and 224 metric tons CO_2/acre, respectively, at these depths.

LB

Area LB was amended in 1998 with 100 dry ton/acre of Denver Metro biosolids cake and 100 tons/acre of limestone. In 2008, soil bulk density was 1.4 g/cm^3, EC was 2.7, and pH was 5.2. The EC and pH values were slightly above and below optimal soil ranges, respectively. The %C for the pellet application (LP) was higher than the biosolids (LB) application, and similarly, the pellet application had the highest %N at both depths. Area LB was subject to animal grazing and had an average biomass of 1,414 kg/ha in the shoots and 1,648 kg/ha in the roots. Area LB soil stored 169 metric tons CO_2/acre in the top 15 cm and 151 metric tons CO_2/acre in the 15-30 cm depth interval.

LC

Area LC is located within 100 feet of an area that was treated with 100 dry tons/acre of Denver Metro biosolids. Based on the pH and carbon results, it appears to have been treated with an amendment; however soil amendment application has not been confirmed. Soil EC was 3.1, bulk density 1.2 g/cm^3, and pH was 5.7; like LB, the EC and pH values for LC are above and below optimal soil ranges. The average biomass was 2,288 kg/ha in the shoots and 1,648 kg/ha in the roots. Area LC was also subject to animal grazing. Area LC soil stored 146 metric tons CO_2/acre in the 0-15 cm depth interval, and 119 metric tons CO_2/acre in the 15-30 cm depth interval.

Table 4. Leadville Results, Fall 2008, 10 years after amendment application

Sample	pH	EC	%C	%N	Bulk density (g/cm^3)	C:N ratio	Mg of C/ha	Metric tons CO_2/ acre
Optimum for soils[1]	5.5 - 8	< 2	--	--	0.5 – 1.4	20 – 40:1	--	--
Biosolids 0 -15 cm (LB)	5.23	2.664	5.88	0.36	1.29	11	114	169
Biosolids 15 -30 cm (LB)	5.59	2.74	4.81	0.32	1.41	13	102	151
Pellets 0 -15 cm (LP)	5.89	2.53	6.37	0.52	1.54	10	147	218
Pellets 15 - 30 cm (LP)	5.83	2.76	6.25	0.51	1.61	11	151	224
Compost 0 -15 cm (LC)[2]	5.7	3.08	5.45	0.29	1.2	15	98	146
Compost 15 -30 cm (LC)[2]	5.46	1.78	4.38	0.29	1.22	14	80	119
Untreated 0 – 15 cm (LU)	3.72	3.13	3.75	0.24	1.09	17	61	91
Untreated 15 – 30 cm (LU)	3.67	2.09	4.16	0.26	0.97	16	61	90
Reference 0 – 15 cm (LR)	5.67	0.48	5.22	0.3	0.79	10	62	92
Reference 15 – 30 cm (LR)	5.74	0.22	2.9	0.14	1.22	10	53	79

Notes: CO_2 = carbon dioxide. C = carbon. cm = centimeter. EC = electrical conductivity. N = Nitrogen. Mg = megagram. ha = hectare. NA = not applicable. g/cm3 = grams per cubic centimeter.

1 Source: Nyle C. Brady and Ray R. Weil 2007. *Nature and Properties of Soils*, 14th Edition. Prentice Hall.

2 Until soil amendment application in this area is confirmed, the results are not being used in the carbon sequestration calculations for this report.

LU

The LU area lies on the edge of an area that had been amended in 1999 with 100 dry tons/acre of biosolid pellets and 100 tons/acre of limestone. Therefore, data collected in this plot was not used as a control. Soil EC was 3.1, pH was 3.7, and bulk density was 1.1 g/cm^3. The pH value was very low relative to optimum soil ranges, and EC was high. Area LU had zero biomass for both the shoots and roots. Area LU stored 91 metric tons CO_2/acre in the 0-15 cm depth interval, and 90 metric tons CO_2/acre in the 15-30 cm depth interval.

LR

Area LR served as the reference site so no amendments were added to the soil. Unlike LC, this area was further assessed to be unimpacted by past mining-related activities. Area LR was the only site with EC values within the optimum range for soil: 0.48 g/cm^3. Soil bulk density was 0.79 g/cm^3, and the pH was 5.7, which are also within optimum soil ranges. Area LR had an average biomass of 2,269 kg/ha in the shoots and 2,235 kg/ha in the roots. LR had an amount of stored carbon equivalent to the LC location for the 0 – 15 cm depth and the lowest stored carbon of all the Leadville locations for the 15- 30 depth; LR stored 92 metric tons CO_2/acre and 79 metric tons CO_2/acre.

Statistical Analysis

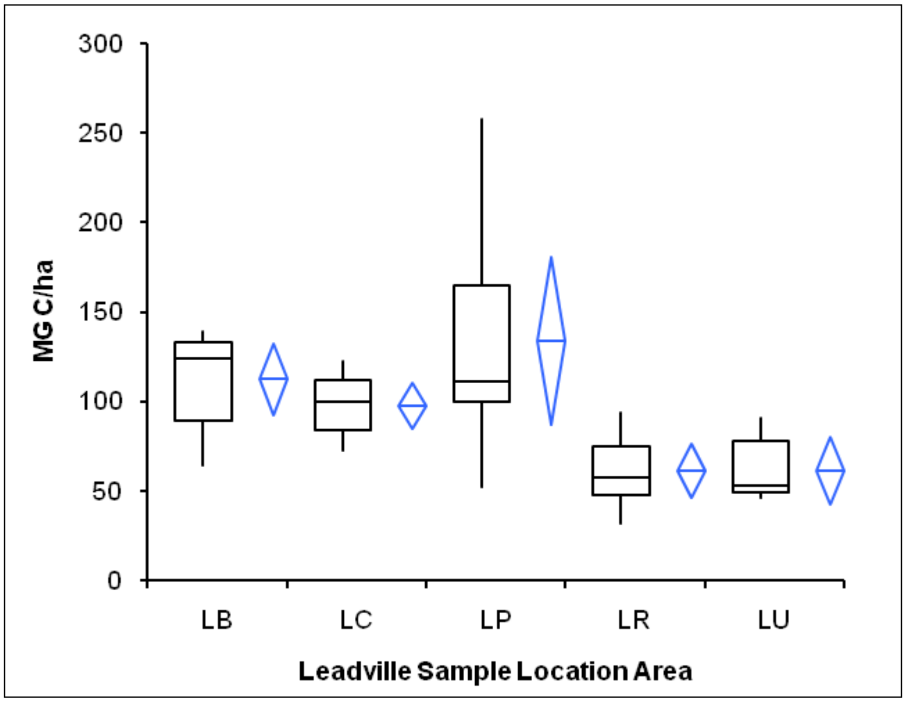
The differences in carbon sequestration potential between the Leadville treatment areas are further illustrated in the box and whisker plots of Figure 5. The plots show elevated medians and means for the treated areas (LP, LB, and LC) relative to the minimally treated and reference areas (LR and LU), though a greater range of values is observed in the treated areas. Limited statistical testing was performed to assess whether the observed differences in the means are statistically significant. The testing began with an omnibus test (1-way analysis of variance [ANOVA]) to assess whether the mean carbon values calculated for the five Leadville areas could be considered equivalent at a 95% confidence level. If the ANOVA rejected equality of means, further testing was performed using post hoc tests to further identify specific treatment areas that differed from the others.

The 1-way ANOVA test for the five Leadville treatment areas indicated that the means are different at a 95% confidence level ($F = 7.35$, $p = 0.0002$); however, application of the Levene's test indicated that one of the assumptions of the ANOVA test (homogeneity of variance) was violated (Levene's = 4.31, $p = 0.006$). Therefore, the finding of unequal means was confirmed through application of Welch's adjustment to the ANOVA test (F ratio = 14.06, $p < 0.0001$), which allows for unequal variance. On this basis further post hoc testing was performed to assess which means or groups of means were different. Dunnett's test was selected for this purpose because it is well suited to assess multiple populations versus a control or reference population. For Leadville, the LU and LR areas were grouped into a single control (untreated) population for comparison to the treated areas LC, LB, and LP. The T3 modification of Dunnett's test was performed, again to adjust for the unequal variances. This test confirmed that LC, LB, and LP were all different from the LU/LR control population above a 95% confidence level ($p = 0.001$, 0.001, and 0.037, respectively).

Statistical testing confirmed a higher level of carbon sequestration potential in the treated areas of the site than in the untreated areas. The statistical tests applied for this evaluation are further described in EPA's data quality assessment guidance (EPA 2006; www.epa.gov/quality/qa_docs.html), and were performed using commercially-available software packages (IBM SPSS Version 18, and the Analyze-It statistical plug-in for Microsoft Excel, Version 2.22). Input data and software output for the statistical evaluations are included in Attachment 1.

Figure 5 (right): Comparative Box and Whisker Plots for Leadville Treatment Plot Data.

Note: The horizontal lines of the black boxes represent the 1st quartile (25th percentile, lower line), 2nd quartile (median, middle line), and 3rd quartile (75th percentile, upper line) of the nine replicate carbon sequestration values (in Mg of C/ha) calculated for each of the sampled Leadville treatment areas. The whiskers of the black boxes extend to show the minimum and maximum values for each area. The blue diamonds show the mean values (horizontal line) and 95% confidence limits (apexes).



Summary

For the 0-15 cm soil depth samples, LP had the largest amount of metric tons of CO_2 per acre at 218, followed by the LB at 169, then LC at 146, and finally the untreated LU and LR areas at approximately 90. Statistical testing verified that the observed differences between the treated areas (LP, LB, and LC) and the untreated areas (LU and LR) were statistically significant at the 95% confidence level. Although statistical evaluations were not performed for the 15-30 cm depth samples, LP was again observed to have the largest amount of metric tons of CO_2 per acre for this depth interval at 224, followed by the LB at 151, then the LC at 119, then LU at 90, and finally LR at 79.

For the 0-15 cm depth, the soil amendment treatments resulted in 169-218 metric tons of CO_2 per acre and the site amended 80 acres (the nature and amount of soil amendments at LC is uncertain, so results for the LC area are not included in this range). For a rough estimate of carbon sequestration in amended Leadville soils, the mean CO_2 concentration was used (178 metric tons of CO_2 per acre, which is the average of the LP and LB values), minus the untreated soil value (91 metric tons of CO_2 per acre), to yield 102 metric tons of CO_2 per acre more than the control over 10 years; or 10.2 metric tons of CO_2/ acre/ year. Multiplying this number (102) by 80 acres gives 8,160 metric tons of CO_2 sequestered over 10 years; or 816 metric tons of CO_2/year. This is equivalent to the amount of carbon sequestered annually by 174 acres of pine or fir forests, or the greenhouse gas emissions avoided by recycling 275 tons of waste per year instead of sending it to a landfill (www.epa.gov/cleanenergy/energy-resources/calculator.html, accessed May 20, 2010). At Leadville, therefore, adding biosolids to the soil created a sink for CO_2.

Stafford

Two locations were selected for soil sampling to determine the rate of carbon in the soil at the Stafford site. One was a high biosolids application area (SH) at 121 dry tons/acre, and the other was a control (SC) were no biosolids were applied. Each location had three sampling grids of 40 feet by 40 feet each. Each grid included five randomly-selected sample points. Four-point composite samples were collected at two depths (0-15 and 15-30 cm) at each point. The sample points were at the same relative locations within each grid, as chosen by picking the same Cartesian coordinates on each 40 feet by 40 feet grid. A composite sample was collected from each sampling point by placing a quartered square sampling template on the ground (Figure 6). One subsample was taken from each quarter and put into a bucket. Once all the subsamples from each quarter were in the bucket, the soil was mixed into a composite sample and then put into sample jars. Samples were analyzed for pH, EC, %C, %N, and bulk density. The mean results for the three locations of SH and SC soil are shown in Table 5.

Figure 6. Stafford Airport, VA Sampling Grid. Photograph courtesy of Ellen Rubin, 2008.

The Stafford sampling and analytical program used the same sampling team and laboratory as the Leadville site (Lockheed Martin and EPA NHEEL). The site was sampled on September 17-18, 2008. Climatic variables at site on September 17, 2008 were: mean temperature of 64 ° F, maximum temperature of 77°F, minimum temperature of 51°F, and no precipitation. On this date, the average wind speed was 1 mph, with a dew point of 53, and an average humidity of 70%.

Climatic variables at site on September 18, 2008 were: mean temperature of 66°F, maximum temperature of 80° F, minimum temperature of 51°F, and no precipitation. On this date, the average wind speed was 0 mph, with a dew point of 54, and an average humidity of 70%.

Table 5 shows that the bulk density results for all samples were within the optimum range for soils (0.5 – 1.4 g/cm^3). The pH was lower than the optimum range for soils (5.5 – 8). The EC was within the optimum range of <2 for soils. The % C for the biosolids application was higher than the control area. The mean concentration for the 0-15 cm depth biosolids application was 1.15%C and the control was 0.3% C. The % N for the biosolids application was also higher than the control area. The mean concentration for the 0-15 cm for the biosolids application was 0.12%N and the control was 0.04%N. Though both the %C and %N were higher in the biosolids application for the 15-30 cm sample than in the control, the differences were not significant. Since the site was amended only six years prior to sampling, it follows that the surface applied organic matter has not yet influenced carbon concentrations at the lower sampling depth. Table 5 also presents the calculated C:N ratio, Mg of C/ha, and the metric tons of CO_2 per acre.

Plant and root biomass data were also collected at the Stafford soil sampling locations. The high biosolids application area had 90 – 100% coverage of a cool season grass, essentially a monoculture, for a majority of the samples (52 out of 54). For a majority of the control plot, 0 -20% had vegetation coverage of a fine fescue with a small percentage of a legume species. The high biosolids application had an average biomass of 3100 kg/ha in the shoots and 1863 kg/ha in the roots. For the control the average biomass for the shoots was 206 kg/ha and for the roots 425 kg/ha. The high biomass coverage will insure continued carbon storage in the soil.

Table 5. Stafford Results, Fall 2008, 6 years after amendment application

Sample	pH	EC	%C	%N	Bulk density (g/cm^3)	C:N ratio	Mg of Carbon/ha	metric tons CO_2/ acre
Optimum for soils[1]	5.5 -8	< 2	--	--	0.5 – 1.4	20 – 40:1	--	--
Pre-amendment	2.34	--	--	0.37	0.03	--	--	--
Piscataway soil amendment	11.9	--	260.7 g/kg	0.4 g/kg	--	13.23	--	--
Biosolids 0 -15 cm (SH)	3.96	1.003	1.15	0.12	0.95	96	16	24
Biosolids 15 – 30 cm (SH)	3.41	1.618	0.47	0.06	1.19	78	8	12
Control 0 – 15 cm (SC)	3.24	1.517	0.3	0.04	1.28	7.5	6	9
Control 15 – 30 cm (SC)	3.07	1.65	0.27	0.04	1.8	7.25	7	11

Notes: EC = electrical conductivity (dS/m = deciSiemens/meter). C = Carbon. N = Nitrogen. Mg = milligram. g/cm^3 = grams per cubic meter. CO_2 = carbon dioxide. Ha = hectare.

1 Source: Nyle C. Brady and Ray R. Weil 2007. *Nature and Properties of Soils*, 14th Edition. Prentice Hall. September 16.

Statistical Analysis

The differences between the Stafford sample locations are further illustrated in the box and whisker plots of Figure 7, which show the elevated median and mean Mg C/ha values for the treated location (SH) relative to the reference area (SC). Application of the Shapiro-Wilk test and the F-test indicated that normality and equality of variance could be assumed in both the SH and SC data sets at the 95% confidence level. On this basis, a t-test was applied to confirm a significant difference in the means of the SH and SC populations ($t = -3.46$, $p = 0.002$). Input data and software output for the statistical evaluations are included in Attachment 1.

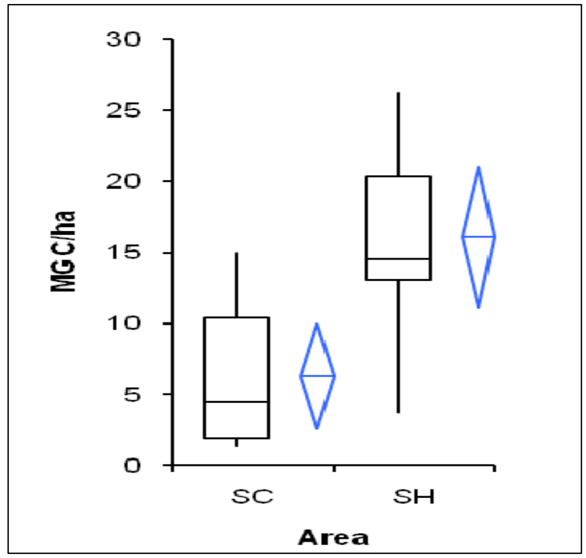


Figure 7 (right). Comparative Box and Whisker Plots for Stafford Treatment Plot Data. Figure shows elevated mean, median, and quartiles for the treated SH area relative to the SC reference area.

Summary

For the 0-15 and 15-30 cm soil depths, the biosolids treatment resulted in 24 and 12 metric tons of CO_2 per acre, respectively. In the control samples, carbon in the 0-15 and 15-30 cm soil depths was 9 and 11 metric tons of CO_2 per acre, respectively. Statistical testing of the surface soil interval (0-15 cm) showed that the difference in sequestered carbon between the treated SH area and the untreated SC area was statistically significant. Because a difference in carbon concentration was seen in 0-15 cm depth, these carbon numbers were used to calculate carbon sequestration rates. Stafford airport amended 275 acres with a gain of 15 (24 minus 9) metric tons of CO_2 per acre more than the control over 6 years; or 2.5 metric tons of CO_2/ acre/ year (Table 3). This is equivalent to the amount of CO_2 emissions associated with 281 gallons of gasoline consumed per year. (www.epa.gov/cleanenergy/energy-resources/calculator.html, accessed May, 2010). Like at Leadville, adding biosolids to the soil created a sink for CO_2 at the Stafford site.

Sharon Steel

Figure 8. Sharon Steel Superfund Site, PA, Pilot Demonstration Test Plots. Photograph courtesy of Bruce Pluta, EPA Region 3.

Sharon Steel has multiple separate pilot demonstration plot areas (Figure 8) that have been constructed to evaluate different soil amendment types and rates. To determine which would be the correct application rate to contain the contaminants, field plot areas were previously evaluated at 10% biosolids (plot areas “10”), 10% biosolids plus pine bark (plot areas “10b”), 15% biosolids (plot areas “15”), 15% biosolids plus pine bark (plot areas “15b”), 15% biosolids plus compost (plot areas “15c”), 15% biosolids plus compost plus pine bark (plot areas “15bc”), 20% biosolids (plot areas “20”), and 20% biosolids plus pine bark (plot areas “20b”). Untreated reference plots were also evaluated (plot areas “0”). For the 0 (reference) plot areas and the plot areas containing 10% and 20% biosolids and biosolids plus pine bark, six replicate 15 feet by15 feet field plots were established for sampling. For the 15% biosolids plot areas, three replicate 15 feet by15 feet field plots were sampled. A single 10-point composite sample was collected from the top 15 cm of soil in each plot.

Sampling and analysis was performed by the School of Environment and Natural Resources, Ohio State University. Samples were collected on September 11 and December 3, 2008. For September 11, the mean temperature was 60^{o}F, the maximum temperature was 77.7^{o}F, the minimum temperature was 44.1^{o}F, and there was no precipitation. On this date, the mean wind speed was 6.1 mph, with a dew point of 48.7^{o}F, and an average humidity of 70%. On December 3, the mean temperature was 31.4^{o}F, the maximum temperature was 45.0^{o}F, the minimum temperature was 24.1^{o}F, and there was no precipitation. On this date there was a mean wind speed of 11.74 mph and a dew point of 19.2^{o}F (www.almanac.com/weather, accessed January 2010).

Most of the samples were collected the day after the plot was established and the biosolids were incorporated. Soil samples were analyzed for pH, EC, %C, %N, and bulk density. The mean results for the sample replicates in each plot type are summarized in Table 6. As shown, the pH for all treatment plot and control samples was quite high, ranging from 9.8 to 12, relative to the optimum pH range for soil (5.5 – 8). The EC was also well above the optimum limit of 2 dS/m high for all the 10% and 20% biosolids plots, but approached this limit for the two compost plots. The bulk density was just above the optimum range (1.4 g/cm^3) for all the plots. The % C and %N were highest for the 15% biosolids/compost samples. Table 6 also presents calculated C:N ratio, Mg of C/ha, and the metric tons of carbon dioxide per acre for all of the plot types sampled. Because the plots were established just before sampling, vegetation was not present on any of the plots and biomass could not be assessed.

Table 6. Sharon Steel Results, Fall 2008, Year 0

Sample (all depths 0 15 cm)	pH	EC (dS/m)	%C	%N	Bulk density (g/cm^3)	C:N ratio	Mg C / ha	Metric tons CO_2/ acre
Optimum for soils[1]	5.5 -8	< 2	--	--	0.5 – 1.4	20 – 40:1	--	--
Control	12	4.92	0.89	ND	1.63	NA	22	32
10% Biosolids	11.9	4.61	0.76	ND	1.64	NA	19	28
10% Biosolids + pine barks	11.8	4.19	1.65	ND	1.58	NA	39	58
15% Biosolids + compost	9.8	2.53	2.27	0.5	1.12	27.3	38	57
15% Biosolids + compost + pine bark	9.9	2.28	3.12	0.497	1.43	19.5	67	99
20% biosolids	12	4.99	1.4	0.331	1.52	16.0	32	47
20% Biosolids + pine bark	12	4.98	1.54	0.296	1.53	21.8	35	52

Notes: EC = electrical conductivity (dS/m = deciSiemens/meter). C = Carbon. N = Nitrogen. Mg = milligram. g/cm^3 = grams per cubic meter. CO_2 = carbon dioxide. Ha = hectare.

[1] Source: Nyle C. Brady and Ray R. Weil 2007. *Nature and Properties of Soils*, 14th Edition. Prentice Hall. September 16.

Statistical Analysis

The differences between the Sharon Steel sample locations are further illustrated in the box and whisker plots of Figure 9. The plots show elevated medians and mean Mg C/ha values for the more highly treated locations (the 15% and 20% biosolids areas, plus the 10% biosolids area with added pine bark) relative to the minimally treated and reference areas (the 0% and 10% biosolids areas), though a greater range of values is observed in some of the treated areas. Limited statistical testing was performed to assess whether the observed differences in populations were statistically significant. The statistical approach was similar to the Leadville site; use of ANOVA to assess equality of means, followed by additional post hoc testing if needed to further evaluate the nature of any differences between the means.

As for the Leadville site, a 1-way analysis of variance (ANOVA) test indicates that the means are different at a 95% confidence level ($F = 5.83$, $p = 0.0001$) for Sharon Steel, but Levene's test (Levene's = 3.283, $p = 0.007$) again indicates the need for the Welch's ANOVA, which confirms a difference in means (F ratio = 4.61, $p = 0.013$). The Dunnett's T3 was used to assess which treatment plot means differed relative to the untreated reference plot (Plot 0). However, the T3 test showed no significant differences between Plot 0 and the other plots at 95% confidence (the minimum p-value of 0.154 for comparison to Plot 0 was reported for the 15bc plot). The power of statistical tests to discern differences between the Sharon Steel treatment areas may be limited by the low numbers of samples that were collected for some areas (three samples for each of the 15% biosolids areas). Input data and software output for the statistical evaluations are included in Attachment 1.

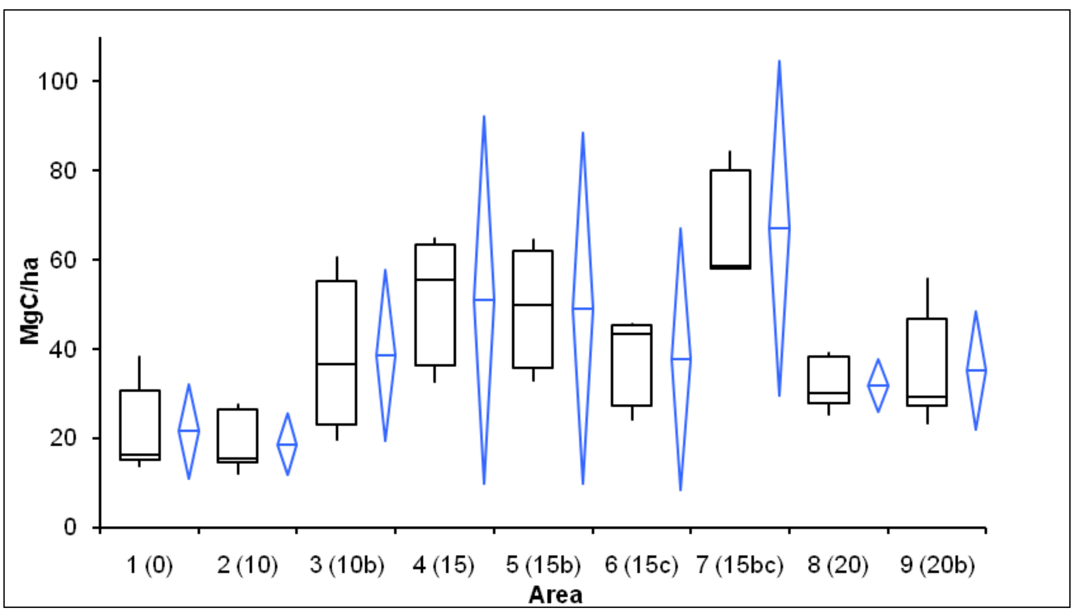


Figure 9. Comparative Box and Whisker Plots for Sharon Steel Treatment Plot Data. The figure shows elevations mean, median, and quartiles, but also high data variability, for some treated areas

Summary

This site is different than the previous two sites reviewed in that it is a demonstration site and the soil amendments were applied immediately before sampling. The carbon calculations are "Time 0" measurements for a one time application of soil amendments. Future sampling is planned so that yearly sequestration rates can be estimated.

Carbon in the analyzed soil was highest for plots with the 15% biosolids application and ranged from 57 – 99 metric tons of CO_2 per acre, compared to control area results of 32 metric tons of CO_2 per acre. Although ANOVA tests verified that the mean carbon values differed between the application areas, further testing showed no differences between any of the treatment areas and the control area (Plot 0) at 95% confidence. Since this is a field demonstration, it has not been determined how many acres will be restored during the final remediation. Therefore, the following assumptions were made in order to calculate the potential for carbon sequestration at this site. The site is 400 acres, but it was assumed that only half the site would be amended. Applying this 200 acre estimate in conjunction an average sequestration estimate of 46 metric tons of CO_2 per acre for the 15% biosolids plots [99 + 57)/2 – 32] produces a potential carbon sequestration estimate of 9,200 metric tons of CO_2 for the site.

Green House Gas Accounting

The sampling and analysis and calculation for this study accounted only for carbon in the soil. For a more complete greenhouse gas accounting, life-cycle analysis, additional emissions factors would need to be considered. Next steps for this research will include focusing on such greenhouse gas (GHG) accounting.

Several organizations (i.e., the Climate Action Reserve, Chicago Climate Exchange, Regional Greenhouse Gas Initiative, etc.) have been created to trade carbon credits. As part of their business plans, some organizations including the Chicago Climate Exchange, the California Climate Action Reserve, and the Clean Development Mechanism have developed protocols that are used to document practices that reduce carbon emissions either through carbon sequestration or emissions avoidance. All three of these exchanges also have protocols for calculating the benefits (avoided emissions) of using organic residuals for soil amendments and preventing them from being disposed in landfills. These protocols give credits for methane avoidance. However, there is no current carbon accounting protocol for sites that have been remediated and restored with soil amendments.

To address GHG accounting considerations, the EPA developed a working draft report "Carbon Sequestration Estimate Calculation Methodology for Soil Amendment/ Re-vegetation Remediation" in 2009. While the working draft report needs review and field testing, it is likely that the types of information it addresses will be used to form a crediting protocol in the future. This study's EPA researchers are collaborating with EPA's Air Program on a scoping exercise to refine the methodology contained in the 2009 working draft report.

Many factors need to be considered when conducting a site carbon accounting system. These include:

- Emissions related to transportation and fossil fuel burning equipment at the site,
- Fate of the soil amendments if not reused at the contaminated site and the associated emissions related to disposal of such amendments,
- GHG emissions produced by decomposition of the soil amendments (i.e. methane [CH_4] and nitrous dioxide [NO_2]0, and
- Other activities at the site that effect the carbon balance of the activity.

Table 7 provides more-detailed lists of parameters to consider in carbon accounting. A useful carbon accounting scenario must show that the carbon is real, additional, permanent, and verifiable. Computer models have been developed to predict soil carbon concentrations and potential for fugitive gas releases from agricultural soils. These models include inputs on soil properties such as: pH, EC, soil type, texture, color, coarse rock fragments, soil compaction, and tree root growth. It is not straightforward to use these models for soil carbon on contaminated land as the surface residual material at many Superfund sites is not a normal soil and may not accumulate carbon in the same way that a 'healthy soil' would. In addition, the large inputs of organic matter used to restore these sites are not considered in the models developed for agricultural soils.

EPA's goal is to account for all types and sources of GHG emissions at our sites, for example CH_4 and N_2O (see Table 7). Denitrification is the conversion of nitrate to nitrogen gas and is a natural process carried out by microorganisms when oxygen is lacking. The Intergovernmental Panel on Climate Change (IPCC) has established default values for N_2O emissions. The default value for composts and biosolids is the same as for synthetic fertilizers, 1% of total N applied. Emissions measurements for N_2O and other GHGs were taken at Sharon Steel, but the results were inconclusive in terms of indicating effects from soil amendment application. In EPA's future efforts, literature values will need to be used.

Table 7. Global Carbon Accounting for Using Soil Amendments for Remediation and Revitalization[1]

Carbon Sinks (i.e. storage)	Greenhouse Gas (GHG) Emission Sources (i.e. CO_2, CH_4, NO_x)
• Vegetation: living biomass (above and below ground), non-living biomass • Soil: organic soil matter; inorganic soil matter • Carbon-rich soil amendments	• Transportation of materials to site • Stationary machinery &other equipment not covered under transportation • Biomass burning for site preparation and management • Fertilizer use • Soil off-gassing

Notes: CO_2 = carbon dioxide, CH_4 = methane; NO_x = nitrous oxide.

[1] Source: IPCC, 2006a, p.1.9; and WRI, 2006.

Though much research remains to be done and further evaluation of sequestration rates is necessary, looking for ways to enhance the amount of carbon stored in the soil is also possible. Best management practices include: erosion control, nutrient management, plant selection, conservation buffers, and correct revitalization methods. Generally, biosolids are only added to the top "O" horizon (Figure 1). However, biosolids can also be incorporated into the subsoil of the land.

Conclusion

Restoring contaminated sites using soil amendments offers potential climate change co-benefits. Emissions can be reduced through reuse of materials that are normally disposed; that is, reusing organic materials that may have been destined for a landfill where they can emit CO_2, CH_4, and N_2O (GHG emission avoidance). In addition, remediation of soil and regrowth of vegetation will lead to terrestrial carbon sequestration of atmospheric CO_2. At disturbed sites, the natural processes of soil and plant nutrient cycling, respiration, and terrestrial carbon sequestration are significantly reduced if not ceased entirely. When carbon-rich soil amendments are applied to these sites, the amendments help to jump-start the soil and plant life cycles. Soil amendments provide a high concentration of carbon to carbon-devoid land, so that the land is transformed to a favorable environment for soil activity and plant growth. In addition to carbon storage in soils, the newly established growth of trees and plants assimilate CO_2 from the atmosphere during photosynthesis. Plant also cycle CO_2 through their roots into the soil, where it is used for soil microbial respiration or stored (i.e., sequestered). These processes lead to the reduction of GHGs in the atmosphere. When using soil amendments for restoration there is both a one-time carbon load at the time of soil amendment application and an annual terrestrial carbon sequestration rate associated with the new functioning ecosystem until the carbon reaches equilibrium.

This study assessed carbon sequestration additionality and rates at three pilot sites. Carbon sequestration rates for the three study sites are estimated as: (1) 8.7 metric tons of CO_2 per acre per year at Leadville, (2) 2.5 metric tons of CO_2 per acre per year at Stafford, and (3) 46 metric tons of CO_2 per acre for the one time demonstration plot at Sharon Steel. As a basis of comparison, sequestration rates for agricultural soil managed as no till are 0.12 metric tons CO_2 per acre per year (that is, 0.3 metric tons CO_2 per hectare per year). The three study sites are diverse and differ in geography/location, weather, soil type, type of contamination, and soil properties. Statistical evaluations verified observed differences in carbon content between treated and reference areas, although the utility of statistical analyses was limited by the small number of samples collected during the pilot study and the high variability in the carbon content and bulk density data obtained in some of the treatment areas.

For the Sharon Steel, site amendments were applied for a field demonstration project in 2008, while the Leadville site applied full scale amendments 13 years ago. Remediation at Stafford occurred between the time of the other two sites, with full scale amendments incorporated six years ago. The Sharon Steel site is located at the border of Pennsylvania and Ohio, while the Leadville site is located at high elevation in the Colorado Mountains, and the Stafford site is located in the hilly, acidic lands of Virginia. The types of sites and their contamination were also very different. The Sharon Steel site was contaminated after manufacturing steel for almost 100 years, the Leadville site was contaminated after active mining for over 100 years, and the Stafford site suffered releases of contamination from acidic soils due to construction activities in 2000. These sites were chosen for their many differences and the results show that all three of the sites in this field demonstration sequestered carbon. The sites were sampled only once during the present study; however, sampling at multiple times following amendment application can assess long-term carbon sequestration benefits for a remediated site (“permanence”).

The field demonstration applied sample collection, analysis, and calculation protocols that have been documented in a Field Study Protocol guide that can be found at www.cluin.org/ecotools. Other researchers desiring to assess carbon sequestration at sites where soil amendments are applied are encouraged to use the Field Study Protocol to provide comparable data sets or to otherwise recommend refinements to this protocol.

Another example of a Superfund site that was remediated and restored with a single application of biosolids in 1997 is the Bunker Hill mining site in Idaho. Here the soil carbon increased from near zero in the control plots to 4 - 6 Mg C/ha (6 - 9 metric tons CO_2/acre) in the treated plots. Two years after application, there was an average of 13% increase in carbon in the soil where biosolids was applied compared to a 0.4% increase in the control plots. This finding indicates that not only can the soil sequester carbon from soil amendment applications, but vegetation can also be established on the restored ecosystem and continue to sequester CO_2 from the atmosphere. Brown and Subler estimated a one-time carbon sequestration rate of 50 - 100 Mg CO_2/ha (20 - 40 metric tons CO_2/acre) for restoring contaminated lands using organic soil amendments. Another way to estimate carbon sequestration rates conservatively would be to assume the degraded land could be restored to background levels.

In conclusion, soil amendments provide environmental remediation and revitalization benefits by sequestering contaminants, reducing bioavailability, and recycling industrial by-products, while jump starting the ecosystem to allow revegetation. Along with the remediation and revitalization benefits of soil amendments, there is a co-benefit of carbon sequestration. The three field carbon sequestration evaluation sites have proven to sequester carbon above control levels after the remediation and revitalization of the land with soil amendments. This benefit of soil amendments could be applicable to Superfund, Brownfields, Federal Facilities, and other contaminated sites. Further field work and literature review will be necessary to establish a range of carbon sequestration values for various contamination sites across the county.

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Bibliography

Birdsey, R.A. (1996) Regional Estimates of Timber Volume and Forest Carbon for Fully Stocked Timberland, Average Management After Final Clearcut Harvest. *In Forests and Global Change: Volume 2, Forest Management Opportunities for Mitigating Carbon Emissions*, eds. R.N. Sampson and D. Hair, American Forests, Washington, DC.

Brady, N.C., and Ray R. Weil (2007) *Nature and Properties of Soils*, 14th Edition. Prentice Hall. September 16.

Brown, S., P. DeVolder, H. Compton, and C. Henry. (2007) "Effect of amendment C:N ratio on plant diversity, cover and metal content for acidic Pb and Zn mine tailings in Leadville, CO. *Environ. Pollution*

Brown, S. C.L. Henry, R. Chaney, H. Compton, and P.S. DeVolder (2003) "Using municipal biosolids in combination with other residuals to restore metal-contaminated mining areas." *Plant and Soil* 249: 203-215.

Brown, S. and P. Leonard (2004) "Biosolids and Global Warming: Evaluating the Management Impacts," *Biocycle*, August.

Franzluebbers, A.J. (2005) "Soil organic carbon sequestration and agricultural greenhouse gas emissions in the southeastern USA." *Soil Tillage Research*. 83:120-147.

IPCC (2000) *Special Report on Land Use, Land-Use Change, and Forestry*, R.T. Watson et al. (eds.), Intergovernmental Panel on Climate Change, Cambridge University Press, p. 184.

IPCC. (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, Volume 4 Agriculture, Forestry and other Land Uses, Chapter 1 Introduction.

IPCC. (2007) *IPCC Fourth Assessment Report* (AR4). www.ipcc.ch

Jenness, N (2001) "Mine Reclamation Using Biosolids." University of Arizona.

Lal, R., J.M. Kimble, R.F. Follett and C.V. Cole (1999) *The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect*. Lewis Publishers.

Lal, R., J. Kimble, and R, Follett (1998) "Land use and soil carbon pools in terrestrial ecosystems, In Management of carbon soils. Lal, R., J. Kimble, and R, Follett (eds) CRC Lewis Publishers, Boca Raton pp 1-10.

Orndorff, Z.W., W. L. Daniels, and D.S. Fanning (2008). "Reclamation of Acid Sulfate Soils Using Lime-Stabilized Biosolids." *Journal of Environmental Quality*. 37:1447-1455

Rice, C. W. (2002) Geotimes. Storing Carbon in Soils: Why and How? July.

Spargo, J.T., M.M. Alley, R.F. Follett, and J.V. Wallace (2008) "Soil carbon sequestration with continuous no-till management of grain cropping systems in the Virginia coastal plain." *Soil & Tillage Research.* 100: 133–140.

Tian, G. T.C. Grantano, A.E. Cox, R.I. Pietz, C.R. Carlson, Jr., and Z. Abedin (2009) “Soil Carbon Sequestration Resulting from Long-Term Biosolids for Land Reclamation” *J. Environ. Qual*. 37:1-14.

Trlica, A. (2010) “Mitigation of Climate Change through Land Reclamation with Biosolids: Carbon Storage in Reclaimed Mine Soils, Life Cycle Analysis of Biosolids Reclamation, and Ecosystem Services with Reforestation." University of Washington: 191.

U.S. Environmental Protection Agency (EPA) (2009) Science Advisory Report “Valuing the Protection of Ecological Systems and Services.” May. http://yosemite.epa.gov/sab/SABPRODUCT.NSF/81e39f4c09954fcb85256ead006be86e/F3DB1F5C6EF90EE1852575C500589157/$File/EPA-SAB-09-012-unsigned.pdf).

West, T.O., and W.M. Post. 2002. “Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis." *Soil Science Society of America Journal*. 66: 1930-1946.