

# CARBON SEQUESTRATION ON MINED LANDS SUPPORTING ABANDONED GRASSLANDS: SOIL ORGANIC CARBON ACCUMULATION AND DISTRIBUTION<sup>1</sup>

Beyhan Y. Amichev<sup>2</sup> and James A. Burger<sup>3</sup>

**Abstract.** Reclaimed surface coal mines in the eastern United States are commonly revegetated with grasses and legumes. The productivity and carbon sequestration potential of the vegetation varies with the condition and nature of the mined site and soil. This study was conducted to determine the distribution pattern of soil carbon stock on 9 mined grasslands reclaimed after the passage of SMCRA in 1977. Mine soil samples of the surface and the subsurface overburden material were collected to approximately 2m depth and chemical and physical soil properties were determined on the less-than-2mm fine sample fraction. Results are presented for the vertical distribution of soil organic carbon concentration (SOC<sub>C<sub>wt</sub>%</sub>), fine earth (<2mm particle size) fraction (Fines<sub>vol%</sub>), coal-derived carbon concentration (Coal<sub>C<sub>wt</sub>%</sub>), and the bulk density of the fine earth fraction (BD<sub>finest, g cm<sup>-3</sup></sub>) down the mine soil profile. The SOC<sub>C<sub>wt</sub>%</sub> ranged between 0.0 and 0.767% and the Coal<sub>C<sub>wt</sub>%</sub> ranged between 0.0294 and 4.53% among all samples. The R<sup>2</sup> of the soil organic carbon content (SOC) predictions (g C m<sup>-2</sup>) was estimated at 60.6% and the shape of the prediction model resembled that of an exponential function. The results for a hypothetical scenario indicated that at an assumed cost of \$24 per 1cm thick spoil layer across 1 hectare of homogenous project area, labeled as cost of SOC analysis within the soil profile, and \$97.4 per Mg of elemental C, labeled as C credits for the analyzed SOC the maximum cost effective sampling depth was 48cm. One third of the total sequestered SOC was located beyond the cost-effective sampling depth for this experiment based on these sample analyses.

**Additional Key Words:** soil organic carbon, coal derived carbon, sampling depth, regression models, cost analysis

<sup>1</sup> Paper presented at the 7<sup>th</sup> International Conference on Acid Rock Drainage (ICARD), March 26-30, 2006, St. Louis MO. R.I. Barnhisel (ed.) Published by the American Society of Mining and Reclamation (ASMR), 3134 Montavesta Road, Lexington, KY 40502

<sup>2</sup> Beyhan Amichev is Graduate Research Assistant, 228 Cheatham Hall (0324), Department of Forestry, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061. Email: [bamichev@vt.edu](mailto:bamichev@vt.edu); James Burger is Professor of Forest Soils, Email: [jaburger@vt.edu](mailto:jaburger@vt.edu).

<sup>3</sup> 7<sup>th</sup> International Conference on Acid Rock Drainage, 2006 pp 13-29

DOI: 10.21000/JASMR06020013

<http://dx.doi.org/10.21000/JASMR06020013>

## **Introduction**

Tens of thousands of hectares of previously productive forestland in the Appalachian region of the United States that produced high value timber, extensive wildlife habitat, and watershed control presently exist as grassland and highland pasture as a result of surface coal mining operations. Coal operators usually choose the least expensive and easiest methods for site reclamation. Hydroseeding to grass (Booze-Daniels et al., 2000) is the most commonly used practice to gain release of their performance bonds (Daniels and Stewart, 2000) since it is less expensive than reforestation. A major drawback of reclaiming mined sites to grassland growing competitive herbaceous species is that this practice reduces the amount of land used to grow productive native forests - the previous land use for nearly every mined site in the Appalachians (Skousen et al., 1994).

Environmental scientists have reported evidence suggesting that there is an interconnection between global warming and anthropogenic emissions of carbon dioxide and methane (ICCT, 2005; Ruddiman et al., 2005). Temperature increases, as well as unusual weather patterns, have been monitored worldwide. These climate changes are attributed to global warming and increased concentrations of green house gasses in the atmosphere, with emphasis on atmospheric carbon dioxide and methane (King, 2004). The latter became an alarming concern amongst researchers in the post-1980 era when terms like “global warming” and “green house gasses” were first introduced to the scientific community (IPCC, 1997). The immediate and quick reaction of various government agencies, research institutions, and universities was to determine ways to sequester atmospheric carbon and increase its storage time in terrestrial, geologic, and oceanic systems (IPCC, 2000).

Total C accumulation by forests including the litter layer, soil organic matter (SOM) (Rodrigue, 2001; Rodrigue et al., 2002), standing timber and long term forest products (IPCC, 2003; Skog and Nicholson, 1998; Spinney et al., 2005), greatly increase the function of forests in reducing atmospheric CO<sub>2</sub>. In his summary of the global carbon cycle Schlesinger (1995) suggests that the potential for enhanced carbon sequestration in terrestrial ecosystems is much greater in forest vegetation than in soils, which makes reforestation and forest fertilization attractive short-term practices for atmospheric CO<sub>2</sub> sequestration on land.

Currently, carbon accreditation of forest development projects is an essential approach to sequestering atmospheric CO<sub>2</sub> under the provisions of the Kyoto Protocol. There are millions of hectares of land disturbed by surface mining across the United States (USDA, 1979) of which 200,000 hectares are located in the East (OSM, 2002). Reforestation projects on these mined lands are regarded by research institutions, government agencies, and private utility companies as a unique opportunity for sequestering large amounts of atmospheric CO<sub>2</sub> in terrestrial carbon forms.

While improved forest management practices may lead to an increase in forest productivity (Rodrigue et al., 2002) and carbon sequestration potential of reclaimed forest lands in the Appalachian and Midwestern coalfields of the United States (Amichev et al., 2004), there are several challenges associated with verifying C stock changes, especially in the soil component of these forest ecosystems. Many soil factors have an effect on SOM accumulation and decomposition in mine soils. Methods of mine spoil placement, and the subsequent development of mine soils influence their productivity and carbon sequestration potential (Chichester and Hauser, 1991).

Conant and Paustian (2002) and Conant et al. (2003) showed that soil C changes can be detected in grassland and cultivated land using current technology and sampling methods for various scales of analysis, ranging from farm-level to the entire nation. However, for systems of higher spatial variability, such as some forested sites in Washington consisting of low C content sandy soils with irregularly distributed pockets of organic C in buried logs, Conant et al. (2003) reported increased minimum detectable differences (MDDs) of 4.9 Mg C ha<sup>-1</sup> and 31.4 Mg C ha<sup>-1</sup>, respectively, for second growth and old-growth forest sites, compared to a MDD of 2 Mg C ha<sup>-1</sup> for cultivated areas, over four years following changes in management or land use.

Likewise, due to their manmade origin and in particular the mining and reclamation methods, the spatial heterogeneity of mine soils could potentially exceed that of natural systems (Sencindiver and Ammons, 2000) leading to potentially unachievable minimum detectable differences in soil organic C over a certain period of time (5-10 years). Therefore additional work is needed to determine the magnitude of MDD and the relative expenses associated with the process of MDD determination for reforestation projects on mined lands.

Modelers of global climate change need accurate and complete soil organic carbon inventories because the soil C pool is the largest component of the global C pool (Jobbagy and Jackson, 2000) following geologic and oceanic C pools, and because it acts as a regulator of atmospheric CO<sub>2</sub> levels (Amundson, 2001). Soil C inventories and analyses are required for soil quality assessments (Sikora and Stott, 1996) and C cycling predictions (Ellert et al., 2002). Soil quality assessments and terrestrial C flux predictions are also needed for state and regional planning by policy developers, agency officials, and regulators.

The objectives of this paper were (1) to determine the distribution pattern and accumulation of soil organic carbon down the mine soil profile and (2) to determine the maximum cost effective depth of SOC analysis on mined lands supporting abandoned grasslands.

## **Methods and Materials**

The current study is part of a larger research project designed to investigate the effect of different forest establishment treatments on coal mined land and the effects of these treatments on the carbon sequestration potential on mined lands. In this paper we only report results from the study sites established near the town of Norton, VA (Fig. 1). The results for the total number of study sites located in the states of Ohio, West Virginia, and Virginia will be reported in a separate manuscript as soon as all analyses are complete. In the following sections we describe the site selection criteria, study area locations, and data collection procedures used in this work.

### **Study area**

All selected sites were on coal-mined land that has been reclaimed to grassland/hayland/pastureland in the period after 1978. The three sites located in Virginia were seeded to a mixture of grass and legume species in the period between summer of 2002 and spring of 2003. The grass species that were observed on the sites were annual ryegrass (*Lolium multiflorum* Lam.), orchard grass (*Dactylis glomerata* L.), foxtail millet (*Setaria italica* (L.) Palib.) and timothy (*Phleum pratense* L.), while the legumes were red clover (*Trifolium pratense* L.), white clover (*Trifolium repens* L.), and birdsfoot trefoil (*Lotus corniculatus* L.).

At each study site we established three replications (blocks) of nine forest establishment treatments (Fig. 1). The trees were planted in April of 2004 following application of the study treatment procedures: herbicide control, tillage, and fertilization. An extensive description of the

experimental treatments and tree survival and growth data from the first growing season were previously summarized by Casselman (2005).

We established 27 treatment plots (50 by 50m size) near the town of Norton, Virginia (Fig. 1). The plots on the site were divided into three blocks of 9 which were selected according to field measures of site acidity, pH (acidic, neutral, and alkaline), and site accessibility. The two main criteria in choosing plot locations per research block were (i) to locate all plots on relatively flat sites with slopes less than 15%, and (ii) to keep the plots adjacent to each other forming as contiguous of matrix as possible. These criteria were chosen in order to minimize equipment transportation between plots, fencing, and other associated costs, and to increase work efficiency.

#### Data collection

We collected soil samples in the period between July and September of 2003 prior to the application of forest establishment treatments, at 5 locations on each plot to two sampling depths, 0-10 cm and 10-30 cm (Fig. 1). All soil samples were stored in paper bags, or open plastic bags in well-ventilated areas, and were either air-dried or oven dried (at 50-60 °C) in order to shorten the drying time. We passed the soil samples through a No. 10 (<2mm) sieve in order to separate the fine earth fraction from the coarse rock fragments. The fine earth component of each soil sample (<2mm) was used for soil carbon content estimation. Total soil carbon was determined with a carbon-nitrogen auto-analyzer (Vario MAX CNS analyzer, elemental, Hanau, Germany).

In August and September of 2003 two to four 2-m deep pits were excavated with a backhoe in representative locations at each site. Each horizon was described and sampled (Jones, 2005). Multiple bulk density samples were collected in each horizon using a modified version of the excavation method of Blake and Hartage (1986). A metal cylinder approximately 5-cm in diameter was used to extract soil from each horizon. The hole was then lined with a thin plastic bag and filled with lead BB's to the original surface level in order to determine the volume of the excavated hole (Jones, 2005). The whole soil bulk density, coarse fragments content (CFC) (>2mm particle size), and the moisture content of the excavated soil were then used to determine the bulk density of the fine earth fraction ( $BD_{\text{fines}}$  in  $\text{g cm}^{-3}$ ) on the oven-dry weight of the soil.

The majority of soil minerals in the Appalachian region were assumed to have a specific gravity of  $2.65 \text{ g cm}^{-3}$  representing that of quartz and approximately the specific gravity of kaolinite ( $2.6 \text{ g cm}^{-3}$ ). This assumption seems valid for most mine soils where an overburden material mostly comprised of crushed sandstone and siltstone material was used as a soil substitute material. Soils derived from sandstone overburden material are mostly comprised of sand size quartz particles and the clay fraction of soils derived from siltstone material is dominated by kaolinite.

#### Data analysis

Pedogenic soil C exists in two forms, SOM and/or plant residues. A unique property of mine soils is the presence of coal and carboniferous rock particles, commonly referred to as geogenic carbon. Depending on their particle size and quality, geogenic carbon particles could have the chemical and physical properties resembling those of soil organic matter, such as their ability to be chemically oxidized (Daniels and Amos, 1982) and to be decomposed by soil microorganisms (Faison, 1993). Because size and quality of geogenic carbon particles is usually a function of their moisture content and amount of impurities contained in individual coal macerals (distinct

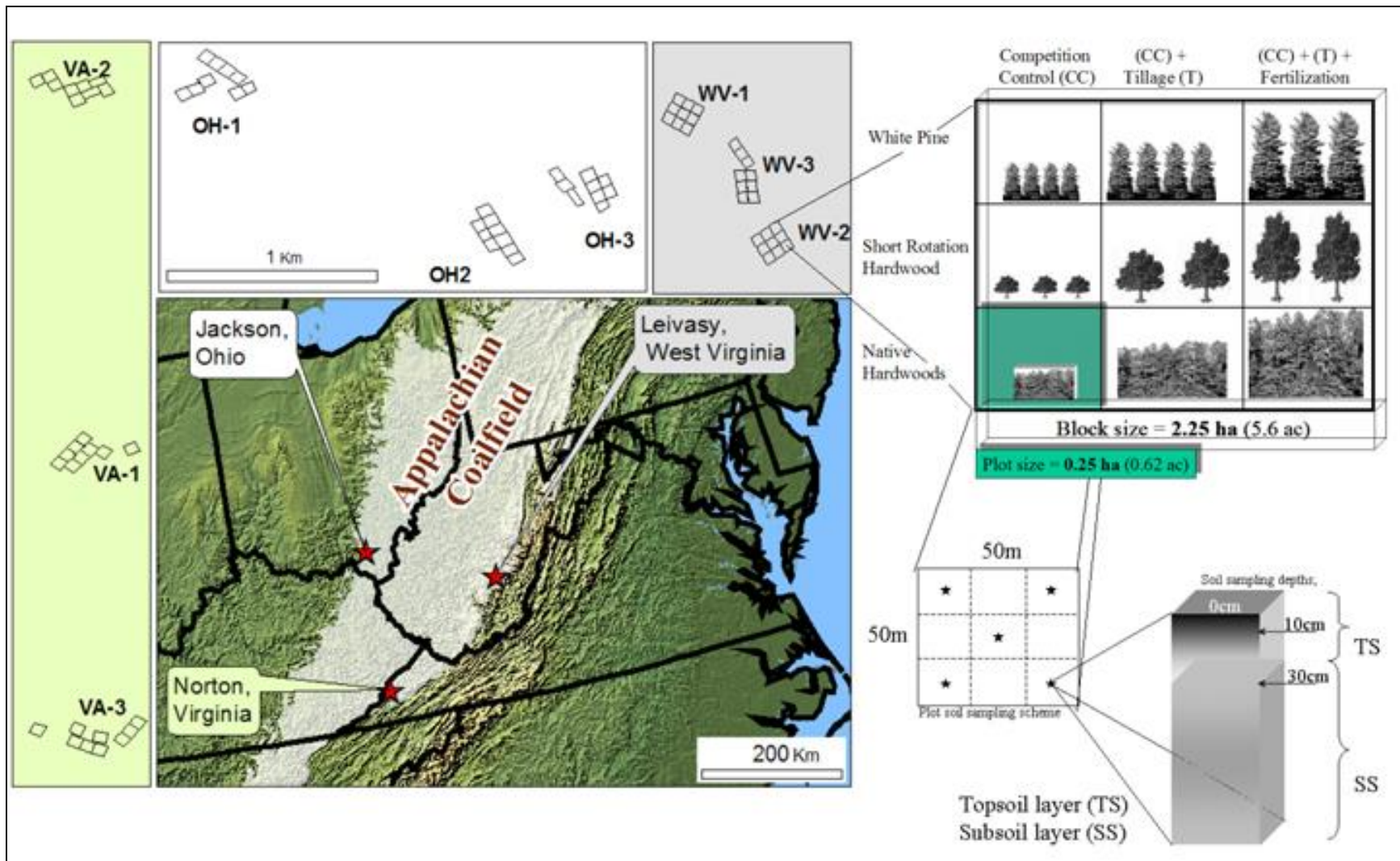


Figure 1. Study site locations, treatment blocks spatial distribution, and data collection scheme for 9 study areas located in Virginia, West Virginia, and Ohio.

organic entities within coal fragments) (Faison, 1993), it is in nearly impossible to predict the presence and distribution of geogenic carbon in the mine soil profile. Before now mine land researchers have used standard soil organic matter measurement procedures, such as the Walkley-Black wet oxidation procedure (Walkley and Black, 1934) for SOM analyses in mine soils with the assumption that coal and carboniferous rock particles are not as easily oxidized as organic matter (Rodrigue, 2001). Although the latter could be true for some mine soils, the effect of the oxidizing agent used in the Walkley-Black procedure could be significant depending on the size and quantity of geogenic carbon particles in the soil (Daniels and Amos, 1982; Skjemstad and Taylor, 1999).

Because of the uncertainties associated with SOM estimates determined by the Walkley-Black procedure and the following adjustment of these estimates in order to acquire the final soil organic carbon content value or the SOC value as referred to in this paper, this method only provides a qualitative measure of SOC and is not recommended for quantitative SOC analysis in soils (Nelson and Sommers, 1982; Skjemstad and Taylor, 1999). Unfortunately, there is no existing method in the literature that may be of use for quantitative estimation of SOC that can successfully differentiate between pedogenic and geogenic carbon forms in mine soils.

The SOC results in this paper are based on the following assumptions; (i) there is an insignificant amount of carbonates present in the mine soil samples, and (ii) the total nitrogen is present in organic forms, such as SOM or coal particles, with negligible or no amounts present as inorganic nitrogen, such as  $\text{NH}_4^+$  or  $\text{NO}_3^-$ . The first assumption was reasonable due to fact that carbonate particles tend to leach very rapidly from young mine soils, which was the case for the study areas in Virginia, and that the average pH values of these soils was below neutral (pH=7) (Jones, 2005). The second assumption was also considered reasonable because of the fact that all of the study sites were in their second growing season, a long enough period for potentially all nitrogen applied as fertilizer at the time of hydroseeding to be either acquired by the vegetation or to leach out of the soil system (Li, 1991).

These two assumptions were used to correct the total soil carbon values measured at a combustion temperature of 900 °C by a carbon-nitrogen auto-analyzer machine where the results included all pedogenic and geogenic carbon forms present in the soil. A C/N ratio of 52.2 for pure coal particles,  $\text{CN}_{\text{coal}}$ , was adopted from previous research work carried out at the same study sites (Li, 1991). An average C/N ratio of 12.0 for the soil organic matter of a grassland soil,  $\text{CN}_{\text{soil}}$ , that is free of carboniferous particles (Chichester and Hauser, 1991; Insam and Domsch, 1988) was adopted for the total C correction procedure depicted below.

The total soil carbon concentration measurements ( $\text{Total\_C}_{\text{wt}\%}$ ) were corrected for coal-derived carbon by solving for the weight percent soil organic carbon concentration,  $\text{SOC\_C}_{\text{wt}\%}$ , and for the weight percent of coal-derived carbon concentration,  $\text{Coal\_C}_{\text{wt}\%}$ , in the following simultaneous equations:

$$\begin{aligned} (\text{Total\_N}_{\text{wt}\%}) &= \frac{(\text{Coal\_C}_{\text{wt}\%})}{\text{CN}_{\text{coal}}} + \frac{(\text{SOC\_C}_{\text{wt}\%})}{\text{CN}_{\text{soil}}} \\ (\text{Total\_C}_{\text{wt}\%}) &= (\text{Coal\_C}_{\text{wt}\%}) + (\text{SOC\_C}_{\text{wt}\%}) \end{aligned}$$

For example, for a soil sample with a measured C/N ratio of 15.0 ( $\text{CN}_{\text{sample}}$ ) and a total sample nitrogen concentration ( $\text{Total\_N}_{\text{wt}\%}$ ) of 0.075% (note that  $\text{Total\_C}_{\text{wt}\%} = \text{CN}_{\text{sample}} * \text{Total\_N}_{\text{wt}\%} = 1.125\%$ ) the  $\text{SOC\_C}_{\text{wt}\%}$  is 0.8328, which is estimated as  $[\text{Total\_N}_{\text{wt}\%} * (\text{CN}_{\text{sample}} -$

$CN_{\text{coal}}/(1-CN_{\text{coal}}/CN_{\text{soil}})]$  and  $\text{Coal\_C}_{\text{wt}\%}$  is 0.2922, which is estimated as  $[\text{Total\_N}_{\text{wt}\%}*(CN_{\text{sample}}-CN_{\text{soil}})/(1-CN_{\text{soil}}/CN_{\text{coal}})]$ . For mine soil samples with C/N ratio lower than 12.0, the sample  $\text{SOC\_C}_{\text{wt}\%}$  was assigned the estimate of the  $\text{Total\_C}_{\text{wt}\%}$  and for samples with C/N ratio greater than 52.2 the  $\text{SOC\_C}_{\text{wt}\%}$  was assigned a value of 0. The latter could occur when denser coal particles with lower moisture content and coal particles of higher aromatic nature dominate the soil sample (Vorres, 1998).

Soil organic carbon content per soil horizon (or per soil layer) with identified upper and lower boundaries was estimated in  $\text{g m}^{-2}$  using the total soil carbon concentration measurements corrected for coal content, the bulk density of the fine earth fraction, the percent content of fine earth fraction on a soil volume basis, and horizon depth, as depicted in the equation below:

$$\text{SOC}_{\text{g m}^{-2}} = [\text{SOC\_C}_{\text{wt}\%}] * [\text{BD}_{\text{fines, g cm}^{-3}}] * [\text{Fines}_{\text{vol}\%}] * [\text{Layer}_{\text{cm}}] \quad \text{Eq.1}$$

where

$\text{SOC}_{\text{g m}^{-2}}$  = soil organic carbon content contained in the volume of soil located within  $1\text{m}^2$  horizontal area and restricted between the upper and lower boundaries of the analyzed soil layer;

$\text{SOC\_C}_{\text{wt}\%}$  = soil organic carbon concentration in the fine soil fraction (Fines, less than 2mm soil particles), measured on a weight percent basis =  $\frac{C_g}{\text{Fines}_g} * 100$ ;

$\text{BD}_{\text{fines, g cm}^{-3}}$  = bulk density of the fines =  $\frac{\text{Fines}_g}{\text{Fines}_{\text{cm}^3}}$ ;

$\text{Fines}_{\text{vol}\%}$  = content of fine earth fraction measured as percent of the total volume of excavated soil sample =  $\frac{\text{Fines}_{\text{cm}^3}}{\text{Soil}_{\text{cm}^3}} * 100$ ;

$\text{Layer}_{\text{cm}}$  = soil layer or soil horizon thickness expressed in cm units.

Propagation of uncertainty. Because SOC estimates are most commonly expressed in units that represent a certain area, such as  $\text{g m}^{-2}$ ,  $\text{kg m}^{-2}$  and  $\text{Mg ha}^{-1}$ , the results of any SOC quantification analysis include the combined error associated with measuring each individual component in Eq. 1. The rules for error propagation described in Harris (2005) were used to produce the 95% confidence limits of individual SOC predictions estimated at 1cm-increments down the mine soil profile. The percent error for  $\text{SOC}_{\text{g m}^{-2}}$  was estimated as the  $\text{SQRT}[(\% \epsilon \text{SOC}_{\text{wt}\%})^2 + (\% \epsilon \text{BD}_{\text{fines, g cm}^{-3}})^2 + (\% \epsilon \text{Fines}_{\text{vol}\%})^2]$ , where the  $\% \epsilon$ -term represents the percent relative uncertainty of the respective variables. Percent relative uncertainty is estimated by dividing the absolute uncertainty, expressed in the units of the variable such as standard deviation or standard error, by the magnitude of the measurement, times 100, i.e.  $\% \epsilon = \text{StdErr} * 100 / \text{Mean}$ .

Statistical analysis and modeling. Statistical procedures for linear regression analysis, proc REG and the C(p) model selection method (SAS, 2004), were used to create prediction models for  $\text{SOC\_C}_{\text{wt}\%}$ ,  $\text{BD}_{\text{fines, g cm}^{-3}}$ , and  $\text{Fines}_{\text{vol}\%}$  by depth for the mine soil profile. All models presented in this paper are statistically significant at the 0.05 alpha level. In addition to model predictions of individual variables, the 95% confidence limits of prediction estimates are also reported.

## **Results and Discussion**

### Vertical distribution of SOC

From various soil horizons at depths ranging from 5 to 150cm from six deep pits excavated to approximately 2m depth, a total of 22 soil samples were sampled and analyzed for their C and N content, (Jones, 2005). At these locations only 10 surface (A-horizon) and subsurface (C or 2C) soil horizons were analyzed for their physical properties, including soil bulk density and CFC measured as weight percent of total soil sample (Jones, 2005). The latter two variables along with the assumption of specific gravity of  $2.65 \text{ g cm}^{-3}$  for soil minerals from this study location were then used to estimate bulk density of the fines and the volumetric percent content of the fines.

Results from the vertical distribution of  $\text{SOC}_{\text{C}_{\text{wt}\%}}$ ,  $\text{Fines}_{\text{vol}\%}$ ,  $\text{Coal}_{\text{C}_{\text{wt}\%}}$ , and  $\text{BD}_{\text{fines, g cm}^{-3}}$  within the mine soil profile are depicted in Fig. 2 and 3. For three of the variables statistically significant regression models were created which explained between 23 % and 54 %, respectively, of the variation of  $\text{SOC}_{\text{C}_{\text{wt}\%}}$  and  $\text{Fines}_{\text{vol}\%}$  within the mine soil profile (Fig. 2a and 2b). Except for one surface horizon, the results indicated that the  $\text{Coal}_{\text{C}_{\text{wt}\%}}$  concentration was approximately 120% of the  $\text{SOC}_{\text{C}_{\text{wt}\%}}$  across all horizons at various depths within the soil profile (Fig. 3a). The  $\text{SOC}_{\text{C}_{\text{wt}\%}}$  concentration ranged between 0.0 and 0.767% while the  $\text{Coal}_{\text{C}_{\text{wt}\%}}$  concentration ranged between 0.0294 and 4.53%.

The distribution of coal-derived carbon within the profile did not follow any particular pattern that could be described by a mathematical model (Fig. 3a). This is most likely due to the fact that most coal particles are very resistant to weathering processes and can move down the soil profile accumulating in the voids created between large rock fragments.

It is of interest to note that the highest concentration of coal-derived carbon was located at the contact zone between the observed subsurface horizons, between the C- and C2- and between the C2- and C3-horizons (Fig. 3a). A possible explanation for this phenomenon is that during the multiple stages of site reclamation and mine spoil placement the upper boundary of the C2- and C3-horizons were heavily trafficked by machinery hauling crushed overburden material and thus became the resting surface for a greater amount of coal particles before the next layer of overburden was hauled to the site and re-spread.

Soil organic carbon concentration decreased exponentially down the mine soil profile but the variation among individual  $\text{SOC}_{\text{C}_{\text{wt}\%}}$  measurements did not permit conclusive inferences about this soil property. The 95% confidence limits of the  $\text{SOC}_{\text{C}_{\text{wt}\%}}$  prediction model indicated that at the lower limit of the predictions there would not be any organic C accumulation beyond a depth of 19cm. On the other hand, the upper limit of the predictions indicated that there will be at least 0.574% (weight percent) soil organic carbon at a depth of 150cm (Fig. 2a).

The latter could be regarded as a computational error if one only takes into consideration the fact that root growth is concentrated in the surface. Because of the excessive compaction of mine soils and type of vegetation, root growth is generally restricted to the surface 1m of the mine soil. However it could be argued that SOC accumulation in subsurface soil horizons at depths greater than 1m could be due to the translocation of dissolved SOC down the profile and its adsorption to the surfaces of fine soil particles located in the voids between larger coarse fragments.



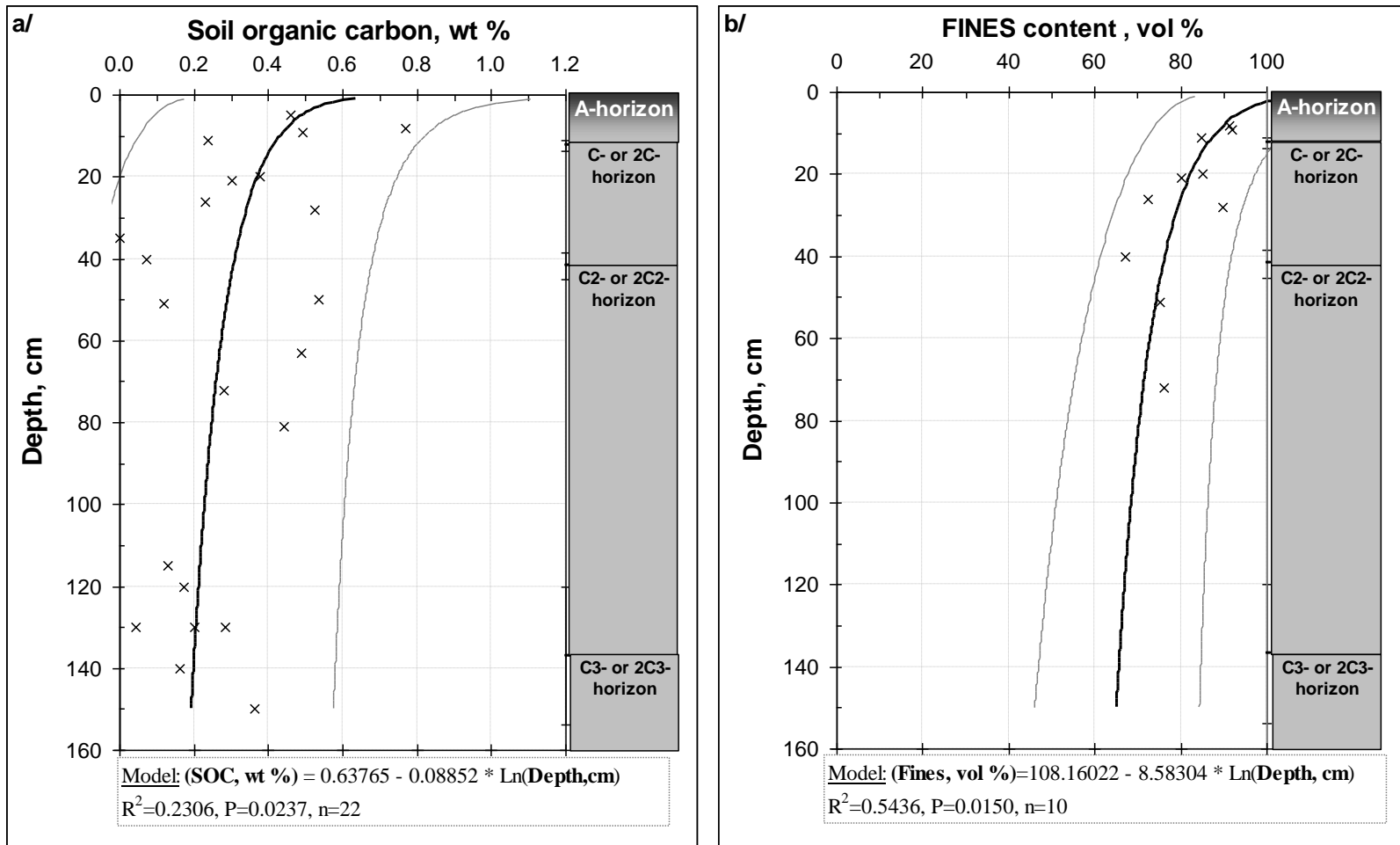


Figure 2. Vertical distribution of (a) SOC<sub>Cwt%</sub> and (b) Fines<sub>vol%</sub>, down the mine soil profile of six deep pits excavated in Wise County, Virginia. Thicker lines indicate the fit of statistically significant prediction models to the data, marked with x's, and lighter lines show the 95% confidence limits of these predictions. The soil profile schemes to the right of each graph indicate the mean horizon boundaries and their associated standard error of the mean.

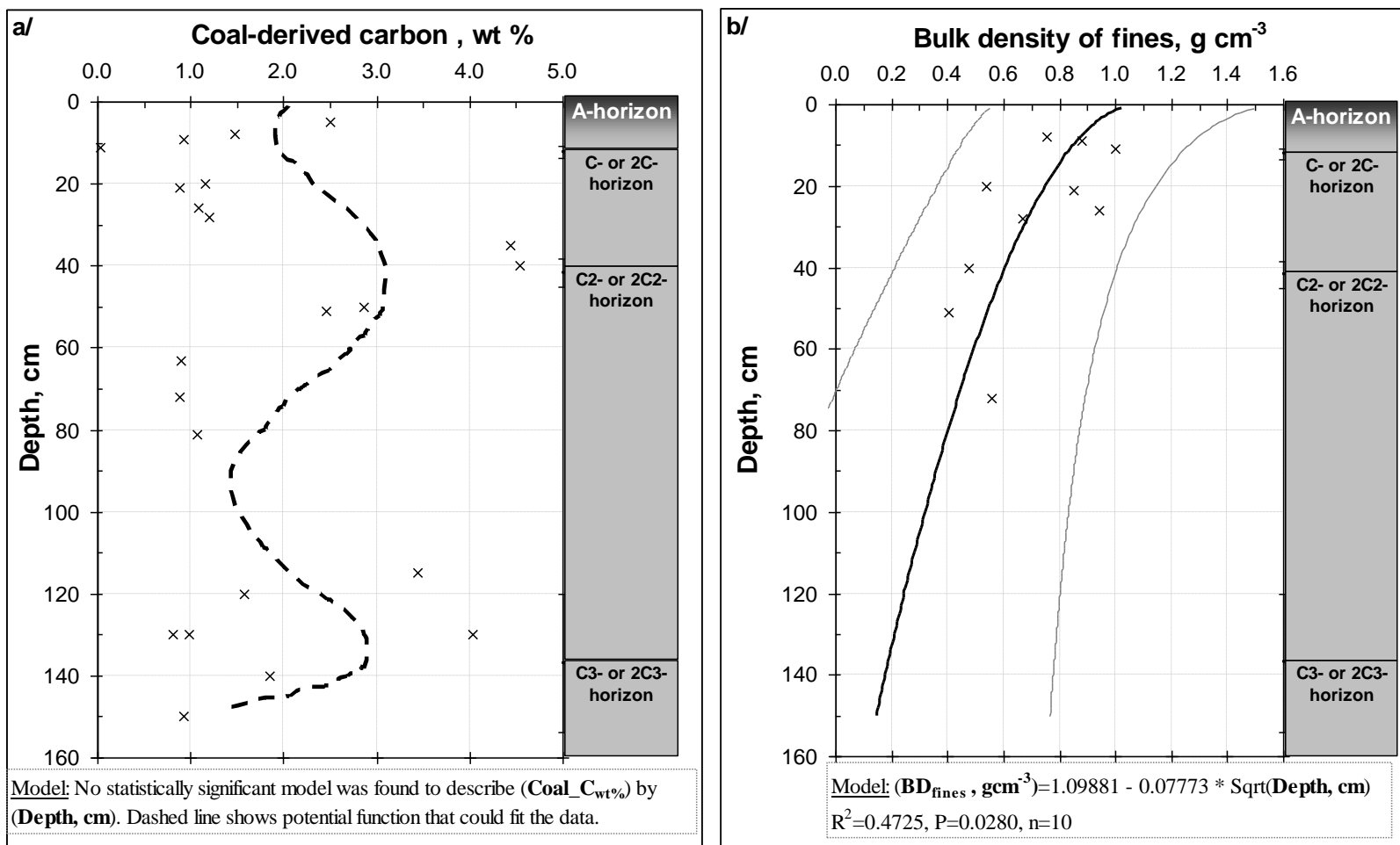


Figure 3. Vertical distribution of (a) Coal\_C<sub>wt%</sub> and (b) BD<sub>finest</sub>, g cm<sup>-3</sup> down the mine soil profile of six deep pits excavated in Wise County, Virginia. Thicker lines indicate the fit of statistically significant prediction models to the data, marked with x's, and lighter lines show the 95% confidence limits of these predictions. The soil profile schemes to the right of each graph indicate the mean horizon boundaries and their associated standard error of the mean.

Depicted in Fig. 2b, the results showed that the volumetric percent of fines decreased exponentially with depth. The 95% lower and upper confidence limits of the  $Fines_{vol\%}$  were 51.0% and 86.2% at 1m depth and 46.0% and 84.0% at 1.5m meter depth, respectively.

These results support the argument that there is a sufficient amount of fines to adsorb dissolved SOC moving from the surface to lower overburden depths. Because the relative decrease of bulk density of the fines was greater than relative decrease of the volumetric content of the fines (Fig. 2b and 3b), one can conclude that a greater frequency of various size voids (free of fine and coarse soil fragments) exist at lower depths. Note that bulk density of the fines was estimated from the whole soil bulk density, which is the soil mass divided by the sample volume after correcting for CFC content, where sample volume is defined as [*CFC volume + fines volume + soil air volume*]. The latter indicates that the soil air volume term was incorporated in the estimates of bulk density of the fines.

Depicted in Fig. 4a are the predicted values for  $SOC_{g\ m^{-2}}$  content estimated by multiplying the individual predictions for  $SOC_{wt\%}$ ,  $Fines_{vol\%}$ , and  $BD_{fines, g\ m^{-3}}$ , from Fig. 2 and 3, as noted in Eq. 1. The 95% confidence limits were estimated using the rules of error propagation, described above, and the resulting predictions were evaluated against the 10 samples for which all three parameters were measured at the same location in the profile. The  $R^2$  of the predictions was estimated 60.6% with the graphical representation of the prediction model resembling that of an exponential function.

A more useful graphical representation of the SOC content results from Fig. 4a is depicted in Fig. 4b. The cumulative SOC content is presented as percent of the total SOC contained within the 0-150cm soil pedon (Fig. 4b). The cumulative SOC content versus soil profile depth could be used to determine the most cost-effective depth for SOC inventory on mined lands. The results from this experimental location indicated that nearly one third of the total SOC on mined lands was found in the surface 0-13cm soil layer while more than two thirds was located in the 0-53cm soil profile. It could be argued that any SOC located in lower depth would be of lesser value due to the higher cost of sample collection, especially in compacted and rocky mine soils.

Undoubtedly, the net monetary value of the sequestered SOC below certain depth, computed as the difference between gross profit from C credits and the measurement costs of the sequestered SOC will become negative and thus undesirable. This is to say that one will pay more money for soil pit excavation, soil sample collection, preparation, and carbon analysis to verify the amount of sequestered SOC below certain soil depths than the actual market gross value of the verified SOC sequestered in the soil.

In an attempt to determine the optimal sampling depth for mined land, one should know not only the variability of SOC within the profile but also the variability across the mined landscape. Assume the following scenario: the cost for excavating, sampling (3 replications), sample preparation, and C analysis for each 5cm-thick soil layer within the profile is \$40 per pit, and the profit for sequestering atmospheric  $CO_2$  is \$97.4 per Mg of elemental C, as indicated by the November 15, 2005 price quote at the European Carbon Market acquired from <http://www.pointcarbon.com>. Also assume that the project area is homogeneous such that only 3 sampling pits per hectare are necessary to estimate the amount of sequestered SOC in units of  $Mg\ C\ ha^{-1}$  at acceptable levels of accuracy and precision. Upon further analysis one could estimate that for this hypothetical scenario the cost for measuring the sequestered SOC within

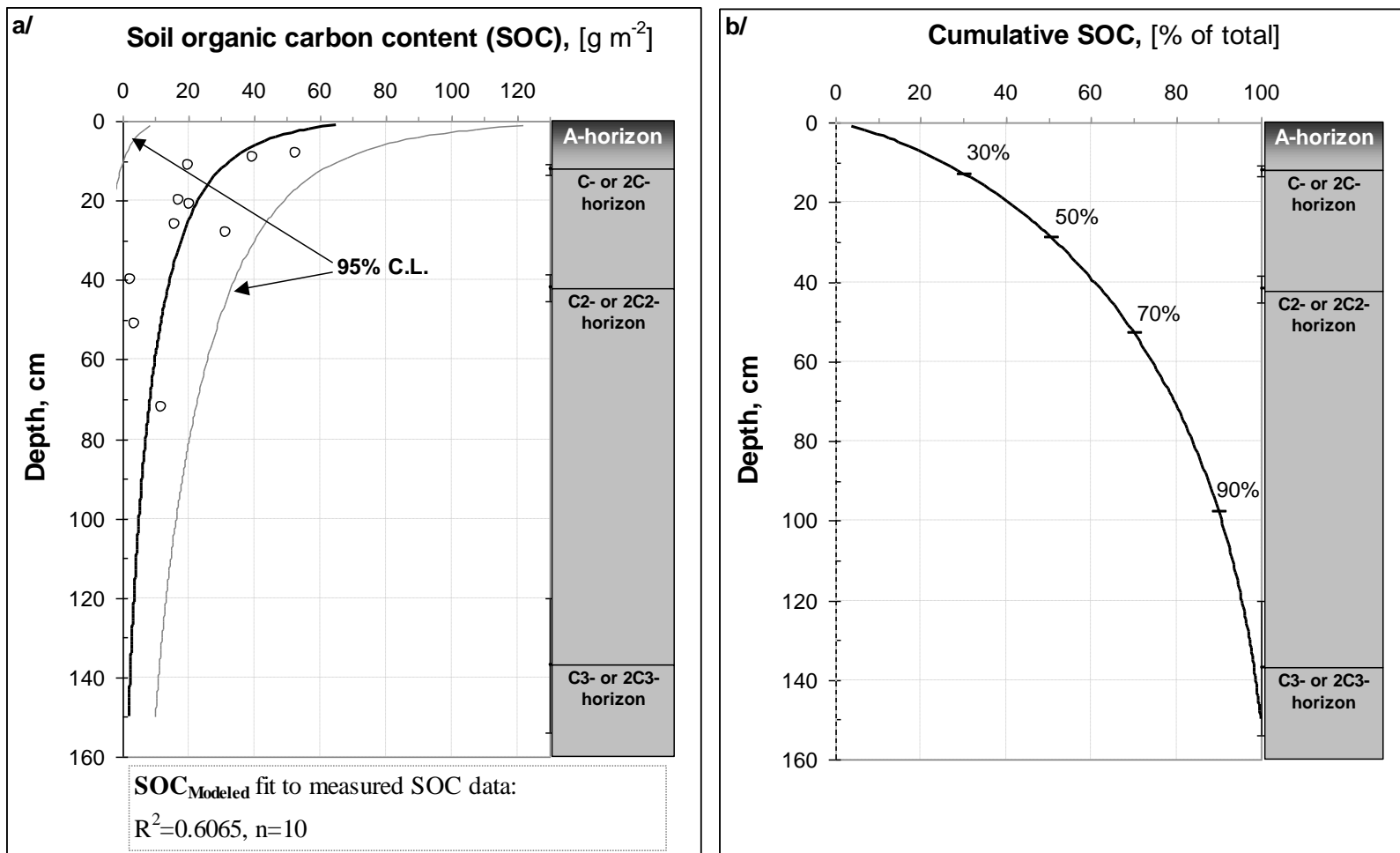


Figure 4. Vertical distribution of (a) SOC  $\text{g m}^{-2}$  (estimated from data in Figures 2 and 3 using Eq. 1) and (b) its cumulative distribution expressed as percent of the total SOC  $\text{g m}^{-2}$  sequestered down the profile within the 0-150cm soil pedon of six deep pits excavated in Wise County, Virginia. Thicker line indicates the fit of a statistically significant prediction model to the data, marked with circles, and lighter lines show the 95% confidence limits of these predictions. The soil profile schemes to the right of each graph indicate the mean horizon boundaries and their associated standard error of the mean.

1cm soil layer across 1 hectare of homogenous area is \$24 (equal to  $\frac{\$40}{5\text{cm} * 1\text{pit}} * \frac{3\text{pits}}{1\text{ha}}$ ).

Therefore in order for a SOC inventorying to be feasible below certain depth the costs for SOC estimation must be lower than the C credit profit from the estimated SOC, i.e. the profit-to-cost ratio  $\$(C_{\text{credit}})/\$(SOC_{\text{inventory}})$  must be greater than 1 (Table 1).

The data in Table 1 depicts the computational steps for selected soil depths leading to identification of the maximum cost-effective depth for SOC analysis for this experimental location. In column *b* depicted are the SOC values for each 1-cm layer within the soil profile while columns *c* and *d*, respectively, depict the cumulative SOC as  $\text{g C m}^{-2}$  and as percent of the whole-profile SOC, to a profile depth indicated in column *a*. For example, the third data row shows that the SOC for the 19-20cm soil layer is  $23.07 \text{ g C m}^{-2}$  and that the cumulative SOC for the 0-20 layer is 712.72, which represents 40.5% of the total SOC contained within the 0-150cm profile. Note that the data in column *b* is also presented in Fig. 4a as the SOC model predictions and the data in column *d* is also presented in Fig. 4b.

Because of the logistics of soil excavation, i.e. before one can collect soil samples from >50cm soil depths one must remove the spoil from 0 to 50cm depth which unmistakably is associated with certain costs, as mentioned above, a new SOC variable (Table 1, column *e*) was estimated to represent the amount of SOC standardized by excavation depth, (column *e*) = (column *c*) / (column *d*)/100. Note that the division by 100 is to convert the  $\text{g m}^{-2}$  units to  $\text{Mg ha}^{-1}$ , which is necessary for the next computational step. The profit-to-cost ratio in column *f* is estimated as (column *e*,  $\text{Mg ha}^{-1} \text{ cm}^{-1}$ ) \* ( $\$97.4 \text{ Mg}^{-1}$ ) / ( $\$24 \text{ cm}^{-1} \text{ ha}^{-1}$ ). Yet again, in order for an SOC inventory to be economically feasible it is desired that at the very least the C credits received for sequestering atmospheric  $\text{CO}_2$  are enough to recover the costs for measuring and reporting the sequestered SOC, i.e. the ratio should be greater or equal to 1.

The results for the assumed scenario indicated that at assumed value amounts for costs of SOC analysis by soil depth ( $\$24/\text{cm}$ ) and for price of the estimated SOC content ( $\$97.4/\text{Mg C}$ ) the maximum cost effective sampling depth is 48cm (Table 1). This is to say that although 1/3 of the total sequestered C is located below 48cm depth (Fig. 4b) one will be losing money if SOC is measured beyond this depth.

## Conclusions

Regression models of chemical and physical soil properties were created in order to estimate the SOC content down the soil profile. Soil organic carbon concentration and volumetric percent of the fines decreased exponentially down the soil profile. The results indicated that one third of the total SOC content on mined lands was found in the surface 0-13cm soil layer and more than two thirds of it was located in the 0-53cm soil profile for the study areas used in this research.

The results for a hypothetical scenario indicated that at assumed costs for SOC analysis within the soil profile equal to \$24 per 1 cm thick spoil layer across 1 hectare of homogenous project area and for C credit profit from sequestered SOC equal to \$97.4 per Mg C, the maximum cost effective sampling depth was 48cm. For this scenario we assumed that the site was homogenous and that only three excavation pits per hectare were necessary to account for the soil variability across space. However this assumption may be invalid due to the manmade nature of mine soils where soil variation can be significant across space. For example, if 6 pits

are necessary to describe the horizontal soil variability on a mined site, as opposed to only 3 pits as was the assumption for a homogenous project area, then the costs will be doubled ( $\$48 \text{ cm}^{-1} \text{ ha}^{-1}$ ) and the cost-effective depth will be reduced to 7 cm allowing only 19.4% of the total sequestered SOC to be measured and reported for C credits.

Table 1. Maximum cost-effective depth for soil carbon content inventory for a hypothetical price scenario of C price equal to  $\$97.4$  per Mg of elemental C, and cost of SOC analysis equal to  $\$24$  per 1cm thick spoil layer across 1 hectare of homogenous project area.

Depth	SOC	Cumulative SOC	SOC standardized by excavation depth		Profit-to-Cost ratio
a	b	c	d	e	f
[cm]	[g m <sup>-2</sup> ]	[g m <sup>-2</sup> ]	[%]	[Mg ha <sup>-1</sup> cm <sup>-1</sup> ]	---
1	65.11	65.11	3.7	0.6511	2.64
10	32.71	444.88	25.3	0.4449	1.81
20	23.07	712.72	40.5	0.3564	1.45
30	17.89	912.88	51.8	0.3043	1.23
40	14.45	1071.87	60.9	0.2680	1.09
47	12.62	1165.48	66.2	0.2480	1.01
48	12.38	1177.87	66.9	0.2454	1.00
49	12.16	1190.02	67.6	0.2429	0.99
50	11.93	1201.96	68.2	0.2404	0.98
60	9.98	1310.18	74.4	0.2184	0.89
70	8.41	1401.09	79.6	0.2002	0.81
80	7.11	1477.86	83.9	0.1847	0.75
90	6.01	1542.79	87.6	0.1714	0.70
100	5.08	1597.65	90.7	0.1598	0.65
110	4.26	1643.83	93.3	0.1494	0.61
120	3.55	1682.44	95.5	0.1402	0.57
130	2.92	1714.39	97.3	0.1319	0.54
140	2.36	1740.43	98.8	0.1243	0.50
150	1.86	1761.21	100.0	0.1174	0.48

There is a need for more efficient C analysis techniques and more advanced methods and tools for horizontal soil variability analyses, such as geographic information systems and geostatistics, in order to minimize the costs for SOC analysis across the landscape and to focus the resources available for SOC measurements deeper in the soil profile where much of the sequestered SOC may be left unreported. Furthermore, the future involvement of the United States and other nations of the world in a global carbon market, similar to that currently established in Europe, would increase the demand for C credits thus increasing the price of the sequestered SOC. As a result, SOC analyses will be economically feasible to greater soil depths meaning that more thorough and complete SOC inventories will be possible. Eventually, the greater good following the establishment of such global carbon market will be the increased

interest in establishing ecosystems with high sequestration potential, such as forest, on disturbed land that otherwise exists as abandoned grassland or fallow land.

### **Acknowledgements**

The authors extend their appreciation to Andy Jones and Chad Casselman for field data acquisition and help with chemical and physical sample analysis and to the Department of Energy (Instrument No: DE-FG26-02NT41619) and to the Powell River Project for sponsoring this research work.

### **References**

- Amichev, B.Y., J.A. Burger, and J.A. Rodrigue. 2004, Carbon Sequestration by Forests and Soils on Mined Land in the Midwestern and Appalachian Coalfields: Preliminary Results, Proceedings America Society of Mining and Reclamation, 2004 pp 20-46  
<http://dx.doi.org/10.21000/JASMR04010020>
- Amundson, R. 2001. The carbon budget in soils. *Annu Rev Earth Planet Sci* 29:535-562.  
<http://dx.doi.org/10.1146/annurev.earth.29.1.535>.
- Blake, G.R., and K.H. Hartage. 1986. Bulk density, p. 365-375, *In* A. Klute, ed. *Methods of soil analysis, Part 1: Physical and mineralogical methods*, 2nd ed. ASA, SSSA, Madison, WI. .
- Booze-Daniels, J.N., W.L. Daniels, R.E. Schmidt, J.M. Krouse, and D.L. Wright. 2000. Establishment of low maintenance vegetation in highway corridors, p. 887-920, *In* R. I. Barnhisel, et al., eds. *Reclamation of drastically disturbed lands*. Agronomy Series No. 41. American Society of Agronomy, Madison, WI.
- Casselmann, C.N. 2005. Effects of Silvicultural Treatments and Soil Properties on the Establishment and Productivity of Trees Growing on Mine Soils in the Appalachian Coalfields. M.S. Thesis, 163p., University Libraries Virginia Polytechnic Institute and State University, Blacksburg, VA. .
- Chichester, F.W., and V.L. Hauser. 1991. Change in Chemical Properties of Constructed Minesoils Developing under Forage Grass Management. *Soil Science Society of America Journal* 55:451-459. <http://dx.doi.org/10.2136/sssaj1991.03615995005500020026x>.
- Conant, R.T., and K. Paustian. 2002. Spatial variability of soil organic carbon in grasslands: Implications for detecting change at different scales. *Environmental Pollution* 116:S127-S135. [http://dx.doi.org/10.1016/S0269-7491\(01\)00265-2](http://dx.doi.org/10.1016/S0269-7491(01)00265-2).
- Conant, R.T., G.R. Smith, and K. Paustian. 2003. Spatial variability of soil carbon in forested and cultivated sites: Implications for change detection. *Journal of Environmental Quality* 32:278-286. <http://dx.doi.org/10.2134/jeq2003.2780> <http://dx.doi.org/10.2134/jeq2003.0278>  
PMid:12549567.
- Daniels, W.L., and D.F. Amos. 1982. Chemical characteristics of some southwest Virginia minesoils [Soil acidity]. *Proceedings / 1982 Symposium on Surface Mining Sedimentology, and Reclamation, Dec 6-10, 1982*; ed G H Graves Lexington, KY:Office of Engineering Serv., College of Engineering, Univ.
- Daniels, W.L., and B.R. Stewart. 2000. Reclamation of Appalachian coal refuse disposal areas, p. 433-459, *In* R. I. Barnhisel, et al., eds. *Reclamation of drastically disturbed lands*. Agronomy Series No. 41. American Society of Agronomy, Madison, WI.

- Ellert, B.H., H.H. Janzen, and T. Entz. 2002. Assessment of a method to measure temporal change in soil carbon storage. *Soil Science Society of America Journal* 66:1687-1695. <http://dx.doi.org/10.2136/sssaj2002.1687>
- Faison, B.D. 1993. The chemistry of low rank coal and its relationship to the biochemical mechanisms of coal biotransformation, p. 1-27, *In* D. L. Crawford, ed. *Microbial Transformations of Low Rank Coals*. CRC Press, Inc., Boca Raton, FL.
- Harris, D.C. 2005. *Exploring chemical analysis*. 3rd ed. W.H. Freeman and Company, New York, NY.
- Insam, H., and K.H. Domsch. 1988. Relationship between Soil Organic Carbon and Microbial Biomass on Chronosequences of Reclamation Sites. *Microbial Ecology* 15:177-188. <http://dx.doi.org/10.1007/BF02011711> PMID:24202999.
- Intergovernmental Panel on Climate Change (IPCC). 1997. *The Regional Impacts of Climate Change: An Assessment of Vulnerability*. (Including Summary for Policymakers). A special Report of IPCC Working Group II.
- Intergovernmental Panel on Climate Change (IPCC). 2000. *Land use, land-use change, and forestry*. (Including Summary for Policymakers). A Special Report of the IPCC.
- Intergovernmental Panel on Climate Change (IPCC). 2003. *Estimation, reporting and accounting of harvested wood products: Technical paper* [Online] <http://unfccc.int/resource/docs/tp/tp0307.pdf> (verified September 14, 2005).
- International Climate Change Taskforce (ICCT). 2005. *Meeting The Climate Challenge: Recommendations of The International Climate Change Taskforce* [Online]. Available by The Center for American Progress [http://www.tai.org.au/Publications\\_Files/Papers&Sub\\_Files/Meeting the Climate Challenge FV.pdf](http://www.tai.org.au/Publications_Files/Papers&Sub_Files/Meeting_the_Climate_Challenge_FV.pdf) (verified August 31, 2005).
- Jobbagy, E.G., and R.B. Jackson. 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecological Applications* 10:423-436. [http://dx.doi.org/10.1890/1051-0761\(2000\)010\[0423:TVDOSO\]2.0.CO;2](http://dx.doi.org/10.1890/1051-0761(2000)010[0423:TVDOSO]2.0.CO;2).
- Jones, A.T. 2005. *Site Quality Classification for Mapping Forest Productivity Potential on Mine Soils in the Appalachian Coalfield Region*. M.S. Thesis, 305p., University Libraries Virginia Polytechnic Institute and State University, Blacksburg, VA. .
- King, D.A. 2004. *ENVIRONMENT: Climate Change Science: Adapt, Mitigate, or Ignore?* *Science* 303:176-177. <http://dx.doi.org/10.1126/science.1094329> PMID:14715997.
- Li, R. 1991. *Nitrogen cycling in young mine soils in Southwest Virginia*. Ph.D. Dissertation, 150p., Virginia Polytechnic Institute and State University, Blacksburg, VA.
- Nelson, D.W., and L.E. Sommers. 1982. Total carbon, organic carbon, and organic matter, p. 539-579, *In* A. L. Page, et al., eds. *Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties*, Agronomy Monograph no.9, 2nd ed. ASA-SSSA, Madison, WI.
- Rodrigue, J.A. 2001. *Woody species diversity, forest and site productivity, stumpage value, and carbon sequestration of forests on mined lands reclaimed prior to the passage of the surface mining control and reclamation act of 1977*. M.S. Thesis, 299p., University Libraries Virginia Polytechnic Institute and State University, Blacksburg, VA. .



- Rodrigue, J.A., J.A. Burger, and R.G. Oderwald. 2002. Forest productivity and commercial value of pre-law reclaimed mined land in the eastern United States. *Northern Journal of Applied Forestry* 19:106-114.
- Ruddiman, W.F., S.J. Vavrus, and J.E. Kutzbach. 2005. A test of the overdue-glaciation hypothesis. *Quaternary Science Reviews* 24:1-10. <http://dx.doi.org/10.1016/j.quascirev.2004.07.010>
- SAS Institute Inc. 2004. SAS software, Version 9.1: SAS Documentation. SAS Institute Inc., Cary, NC, USA.
- Schlesinger, W.H. 1995. An overview of the carbon cycle, p. 9-25, *In* R. Lal, et al., eds. *Advances in Soil Science: Soils and Global Change*. CRC Press, Inc., Boca Raton.
- Sencindiver, J.C., and J.T. Ammons. 2000. Minesoil genesis and classification, p. 595-613, *In* R. I. Barnhisel, et al., eds. *Reclamation of drastically disturbed lands*. Agronomy Series No. 41. American Society of Agronomy, Madison, WI.
- Sikora, L.J., and D.E. Stott. 1996. Soil organic carbon and nitrogen, p. 157-168, *In* J. W. Doran and A. J. Jones, eds. *Methods for assessing soil quality*. Soil Science Society of America Special Publication 49. Soil Science Society of America, Madison, WI.
- Skjemstad, J.O., and J.A. Taylor. 1999. Does the Walkley-Black Method determine soil charcoal? *Communications in Soil Science and Plant Analysis* 30:2299-2310. <http://dx.doi.org/10.1080/00103629909370373>.
- Skog, K., and G. Nicholson. 1998. Carbon cycling through wood products: the role of wood and paper products in carbon sequestration. *Forest Products Journal* 48:75-83.
- Skousen, J.G., C.D. Johnson, and K. Garbutt. 1994. Natural revegetation of 15 abandoned mine land sites in West Virginia. *Journal of Environmental Quality* 23:1224-1230. <http://dx.doi.org/10.2134/jeq1994.00472425002300060015x>  
<http://dx.doi.org/10.2134/jeq1994.2361224x>.
- Spinney, M.P., S.P. Prisley, and R.N. Sampson. 2005. Evaluation of loblolly pine plantation management regimes for wood production and carbon sequestration. *South J Appl For* (in review).
- U. S. Office of Surface Mining (OSM). 2002. State and Indian Regulatory Program Permitting: 2001 [Online] <http://www.osmre.gov/progpermit01.htm> (verified September 14, 2005).
- U.S. Department of Agriculture (USDA) - Soil Conservation Service. 1979. The status of land disturbed by surface mining in the united states: Basic statistics by state and county as of July 1, 1977. National Technical Information Service. SCS-TP-158, Springfield, VA.
- Vorres, K.S. 1998. Coal, p. 1221-1256, *In* A. R. Meyers, ed. *Encyclopedia of environmental analysis and remediation*. John Wiley & Sons, Inc.
- Walkley, A., and I.A. Black. 1934. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science* 37:29-38. <http://dx.doi.org/10.1097/00010694-193401000-00003>.