CARBON SEQUESTRATION BY FORESTS AND SOILS ON MINED LAND IN THE MIDWESTERN AND APPALACHIAN COALFIELDS OF THE U.S.

Beyhan Y. Amichev, Ph. D. [1]
James A. Burger, Ph. D. [2]
Jason A. Rodrigue [3]

[1]Department of Soil Science, University of Saskatchewan,
51 Campus Drive, Saskatoon, SK, S7N 5A8, Canada;
Email: beyhan.amichev@vt.edu.

[2]Department of Forestry, Virginia Polytechnic Institute and State University,
228 Cheatham Hall (0324), Blacksburg, VA 24061, USA.

[3]USDA Forest Service, Allegheny National Forest,
Bradford Ranger District, Bradford, PA 16701, USA

This paper was published in the Forest Ecology and Management Journal:
Amichev, B.Y., Burger, J.A., Rodrigue, J.A., 2008. Carbon sequestration by forests and soils on mined land in the Midwestern and Appalachian coalfields of the U.S. Forest Ecology and Management 256, 1949-1959. (doi:10.1016/j.foreco.2008.07.020)

ABSTRACT

Carbon (C) accreditation of forest development projects is one approach for sequestering atmospheric CO_2, under the provisions of the Kyoto protocol. The C sequestration potential of reforested mined land is not well known. The purpose of this work was to estimate and compare the ecosystem C content in forests established on surface, coal-mined and non-mined land. We used existing tree, litter, and soil C data for 14 mined and 8 adjacent, non-mined forests in the Midwestern and Appalachian coalfields to determine the C sequestration potential of mined land reclaimed prior to the passage of the Surface Mining Control and Reclamation Act (1977). We developed statistically significant and biologically reasonable models for ecosystem C across the spectrum of site quality and stand age. On average, the highest amount of ecosystem C on mined land was sequestered in pine stands (148 Mg ha^{-1}), followed by hardwood (130 Mg ha^{-1}) and mixed stands (118 Mg ha^{-1}). Non-mined hardwood stands sequestered 210 Mg C ha^{-1}, which was about 62% higher than the average of all mined stands. Our mined land response surface models of C sequestration as a function of site quality and age explained 59, 39, and 36% of the variation of ecosystem C in mixed, pine, and hardwood stands, respectively. In pine and mixed stands, ecosystem C increased exponentially with the increase of site quality, but decreased with age. In mined hardwood stands, ecosystem C increased asymptotically with age, but it was not affected by site quality. At rotation age (60 yr), ecosystem C in mined hardwood stands was less on high quality sites, but similar for low quality sites compared to non-mined hardwood stands. The overall results indicated that the higher the original forest site quality, the less likely C sequestration potential was restored, and the greater the disparity between pre- and post-mining C sequestration stocks.

Key words: soil organic carbon, mine soils, biogeochemistry of C, forest productivity, site quality, coal mining

INTRODUCTION

Within the eastern regions of the United States (U.S.), about 650 x10^3 ha have been surface-mined for coal (OSM, 2007). This amounts to a major transformation of regional landscapes in ways that affect terrestrial carbon cycles (Vitousek et al., 1997). Coal mining and the use of the mined coal for power generation are two major sources of carbon dioxide (CO_2) in the atmosphere. In addition to coal combustion, surface mining for coal contributes further to CO_2 emissions because it totally removes the forest vegetation. Some forest biomass is harvested, but most is bulldozed in piles and burned.

Under the provisions of the Kyoto Protocol, numerous countries worldwide agreed to mitigate global climate change by controlling greenhouse gases (GHGs). The governments and industries of these nations would reduce GHGs by sequestering atmospheric CO_2, or by reducing CO_2 emissions (Wright et al., 2000). Carbon (C) accreditation of forest establishment (afforestation and reforestation) projects is one approach for sequestering atmospheric CO_2 (United Nations, 1998). Forests provide a low-cost method of C accreditation compatible with other environmental, economic, and social development projects (Wright et al., 2000). Forest establishment projects use trees to sequester C for long-term storage. As young forests develop, atmospheric CO_2 is locked into wood during growth and stored in litter layers and the soil. However, the C sequestration potential of a forest ecosystem depends on initial soil organic carbon (SOC) content, stand growth rates, the site's biological carrying capacity, stand age, and product utilization. In particular, C sequestration and storage may be increased significantly if forests are harvested and trees are converted into wood products (Skog and Nicholson, 1998). Immediately after harvesting following stand regeneration, new forests will begin growing, and continue sequestering additional amounts of atmospheric CO_2, while the C in previously harvested biomass would be kept locked in wood products for a certain period of time.

Some researchers suggest that sequestration of C in tree biomass and litter is a delaying tactic that only buys time for finding more permanent solutions for C sequestration (IPCC, 2000). However, a compelling argument can be made for restoring forest land mined for coal to C-rich forests that existed prior to mining. The new forest will absorb some of the CO_2 emitted from the coal for which the original forest was sacrificed. Making an effort to maximize the productivity of the restored forest is also worthwhile because forest C pools can vary five-fold within a local edaphic gradient as a function of site quality (Burger and Zipper, 2002). New, productive forests will enhance the site's ability to recapture the C contained in the original forest, and some of the C contained in the coal that was mined beneath it.

Because the C sequestration potential of forested mined land is not well known, it must be characterized in order to make comparisons with other C sequestration projects, and to better understand the differences in C capture levels under varying forest and mined land conditions. Therefore, we characterized fourteen mined and eight adjacent non-mined forests throughout the Midwestern and Appalachian coal regions to accomplish the goals of this study. Our objectives were to: (1) estimate and compare the ecosystem C content on mined forest land with that of non-mined forest land; (2) determine the effects of site quality and stand age on the C sequestration potential of forested mined land; and (3) develop empirical models for C sequestration in tree biomass, litter layer, and soil of coniferous and deciduous forests established on mined land.

MATERIALS AND METHODS

Carbon Data Set

Fourteen reforested mined sites reclaimed prior to the passage of the Surface Mining Control and Reclamation Act (SMCRA) of 1977, and eight adjacent non-mined reference forests were inventoried (Rodrigue et al., 2002; Rodrigue and Burger, 2004). The study was designed using a retrospective research approach of evaluating long-term response of forests to treatments imposed at an earlier time (Burger and Powers, 1991). The initial studies using the stand and soil data sets reported the effects of site quality on tree growth (Rodrigue et al., 2002) and long-term forest productivity on coal-mined land (Rodrigue and Burger, 2004). In this paper, we present improved C inventory results (at current stand age and projected to a rotation age of 60 yr), based on recent allometric equations by forest type (pine, hardwood, mixed), and we report C sequestration empirical models for forests and soils as a function of stand age and site quality on coal-mined land.

Forest vegetation and litter layer plots were selected, described, measured, and sampled. Briefly, the fourteen mined and eight adjacent non-mined sites were located in seven states (Virginia (VA), West Virginia (WV), Pennsylvania (PA), Ohio (OH), Indiana (IN), Kentucky (KY), and Illinois (IL)) across the Midwestern and Appalachian coalfields of the U.S., each with an average size of 2.5 ha of contiguous forest cover. A 20 x 20 m grid was superimposed across each forest so that the site's micro-topography was taken into account; a 20 m buffer strip was maintained on all edges. Within each mined and non-mined forest, four measurement plots were randomly selected at grid intersections. Tree, litter, and soil data were collected from each plot independently from all other plots between May and August 1999; two of the sites were measured in August 1998. Rodrigue (2001) determined stand age using tree cores, measured tree diameter at breast height (DBH, measured at 1.4 m height), total tree height, and litter layer biomass on each plot. Trees in the main canopy greater than 13.0 cm in DBH were tallied within a 404 m^2 circular area. Litter layer biomass was determined from four 0.25 m^2 random samples collected within the 404 m^2 circular area and bulked to form a 1 m^2 sample. Bulked samples were dried, ground, and total C (corrected for ash) was measured with a Leco C analyzer (LECO Corp, St. Joseph, MI). At the center of each plot, Rodrigue (2001) dug a soil pit (to 1.5 m depth) to characterize mine soil development, and collect loose soil samples and duplicate bulk density samples (using cores) from each soil horizon. In the laboratory, soil samples were air-dried, passed through a 2 mm mesh screen to separate the fine soil fraction (<2 mm soil particles) and the coarse rock fragments (>2 mm soil particles). Soil properties were analyzed on the fine soil fraction and soil bulk density was corrected for coarse rock fragments.

Soil organic C content was initially measured using the Walkley-Black (WB) wet oxidation procedure (Nelson and Sommers, 1982), assuming that soil coal fragments would not interfere with the analysis. However, some studies have shown that such interference could exist (Daniels and Amos, 1982). In order to account for the effect (i.e. potential overestimation) of coal fragments on these SOC values, we corrected the Walkley-Black soil organic C (WB-SOC) estimates using a coal-correction equation developed by Amichev (2007). This linear regression equation was designed to estimate SOC concentration from measured WB-SOC values in mine soils originating from sandstone, siltstone, or approximately 50:50% mixture of sandstone and siltstone mine spoil materials. Coal-corrected

SOC(wt%) estimates were converted to per-area values (Amichev, 2007), using bulk density of the fines (<2mm soil particles), volume of the fines, and layer depth data for each soil pit.

Estimation of C Pools

We created three separate data sets for pine, mixed pine and hardwood, and hardwood forests growing on mined land. Pine stands were defined as forest stands in which the basal area (BA) of all hardwood trees, BA_{HW}, was lower than or equal to 20% of the total stand basal area, i.e. $BA_{HW} <= 20\%$; mixed stands were defined as forest stands with BA_{HW} ranging from 20 to 80%; and hardwood stands were defined as forest stands with $BA_{HW} >= 80\%$. Using plot BA as a criterion for tree stocking (Wenger, 1984), we determined whether any stands were inadequately stocked, and whether the reasons for the observed stocking anomalies could be justified. Inadequate stocking means that there were too few surviving trees to use existing site resources. Inadequately stocked plots that were confirmed as data outliers were removed from the data set before performing any data analysis.

For all measurement plots, we estimated total tree biomass (dry weight) using the species-specific tree DBH data. These estimates were based on regression equations described in Jenkins et al. (2003). Total tree biomass included stem wood, stem bark, foliage, treetops, branches, stumps, and coarse roots. Biomass values, including tree and litter layer biomass, were converted to C stocks using conversion factors for different regional species groups (Birdsey, 1992). Total tree C (referred to as tree C hereafter), litter layer C (referred to as litter C hereafter), and coal-corrected SOC estimates were all converted to metric tons per hectare (Mg C ha^{-1}), and summed to produce an ecosystem C estimate. Carbon in ground-layer woody (underbrush) or herbaceous biomass was not included in our analysis because C estimates could not be generated for this portion of the forest ecosystem. However, C contained in these understory components is often ignored in biomass estimates, as it represents only 1 to 2% of the above-ground C content (Birdsey, 1992). Our methodology did not account for fine-root (< 0.2 cm) biomass due to the scarcity of root biomass equations in the literature. Jenkins et al. (2003) reported that most researchers do not define root size, and published equations are for roots with minimum diameters between 0.15 and 5 cm. Jackson et al. (1997) estimated that, at a global scale, the C content in total fine-root biomass approximates 5% of the atmospheric C pool. However, at a smaller scale (forest stand), reports show that average C content in live fine-root biomass in temperate forests ranged from 2.1 to 2.4 Mg ha^{-1} (Jackson et al., 1997), representing only 3 to 4% of the C in live tree biomass (including coarse roots) of forests in the eastern U.S., an average of 64 Mg C ha^{-1} (Turner et al., 1995).

We used site index (SI) to indicate site quality in our study sites (Avery and Burkhart, 1994b); in the remainder of this paper, we used the terms SI and site quality interchangeably to refer to site productivity. Site index is the height of dominant and co-dominant trees within a forest stand at a certain base age (age 50 yr for deciduous and 25 yr for coniferous species). Site index data for each plot were obtained from Rodrigue (2001), who converted the SI of measured trees from various species (across all plots) to the SI of a single species, *Quercus alba* L. (white oak) at base age 50 yr (Doolittle, 1958), using SI tables and graphs that were most suitable for each plot's location (Carmean et al., 1989). White oak was selected because it is native on all sites used in this study, and is an important commercial species in the Midwestern and Appalachian regions.

To determine the effects of site quality and stand age on the C sequestration potential of mined land (by forest type), we used standard regression procedures (PROC REG and the Mallow's Cp model selection option) in SAS® to generate response surfaces where SI and Age were independent variables, and ecosystem C was the dependent variable (SAS, 2007). We based our analyses on well-established and widely-used tree growth and yield models (Nelson et al., 1961; Brender and Clutter., 1970). The general form of these models was:

$$Ln(Eco\_C) = b_0 + b_1(SI) + b_2(Age) + b_3(SI^2) + b_4\left(\frac{1}{Age}\right) + b_5\left(\frac{1}{Age^2}\right) + b_6\left(\frac{SI}{Age}\right) \qquad \text{(Eq.1)}$$

where *Ln(Eco_C)* = natural logarithm of ecosystem C content (Mg C ha^{-1}); b_i = regression coefficient, i=0,1,2,…,6; *SI* = site index; *Age* = stand age.

Testing for Auto-correlated Data

We used geostatistical analyses (Robertson, 1987) to test for the possibility of auto-correlation (dependence with respect to separation distance between individual plots) of our data. We estimated the semivariance statistic $\gamma(h)$ for a range of distance intervals (Robertson, 1987; SAS, 2007) to determine the spatial structure (magnitude of data auto-correlation) of our data, which was computed as the ratio between the semivariance at short distances and the semivariance at larger distances between measurement plots.

Due to the lack of exact latitude and longitude coordinates for each plot, we digitized on-screen (in ArcGIS ™ software) the locations of all plots using detailed stand maps reported by Rodrigue (2001). Four mined and four non-mined plots in southern West Virginia were excluded from the geostatistical analyses as their locations were not available. During the digitizing process, we represented the best approximation of the distances between closely sampled locations within each stand. The separation distances between closely sampled locations were used to test for auto-correlated data. Overall, due to the absence of spatial structure (<23%), for all parameters in the mined and non-mined sites used in this study, the plot-level data were statistically independent, and were suitable for regression analyses.

Rotation Age C Sequestration Empirical Models for Soil, Litter Layer, and Tree Biomass in Coniferous and Deciduous Forests on Mined Land

We developed linear regression models using standard regression procedures (PROC REG, Mallow's Cp model selection option) in SAS® software, in which the independent variable was SI, and the dependent variable (by forest type) was: (i) 60-yr projected ecosystem C; (ii) 60-yr projected tree C; (iii) 60-yr projected litter C; or (iv) 60-yr projected SOC. We developed these models for stands on mined and non-mined land. We selected all final models to be statistically significant (P<0.05 for nearly all models, i.e. 95% probability level, or P<0.10, i.e. 90% probability) and biologically reasonable. To develop these empirical models, we projected the current C pools in all plots to the C pools expected at rotation age 60-yr (one hardwood rotation). Foresters define rotation age as the number of years between the time a stand regenerates, or is planted, and the time when the mature trees can be harvested for timber (Nyland, 1996).

For a selected 60-yr period, we assumed that pine and mixed stands would be harvested twice, at ages 30 and 60 yr, while hardwood stands (on mined and non-mined sites) would be harvested once at age 60 yr.

Projected Tree Biomass C

We used the tree age projection techniques described by Rodrigue (2001) to 'increase' and 'reduce' the present tree biomass of mined and non-mined forest stands to the biomass levels expected at age 60 yr. The age projection method allowed the prediction of DBH increments for a wide range of tree species based on the individual tree measurements of stem core for the last 10 yr of stand development (Rodrigue, 2001):

$$Ln(Core_{10}) = b_0 + b_1 * \left(\frac{1}{DBH_{10}} \right) \qquad \text{(Eq.2)}$$

where Ln($Core_{10}$) = natural logarithm of the 10-yr DBH increment; b_0 = intercept coefficient; b_1 = slope coefficient; DBH_{10} = tree diameter at breast height outside bark at 10 yr prior to current age. Species with low occurrences on the study sites that had similar growth characteristics were grouped together. We used these species-specific (or species group-specific) equations (Rodrigue, 2001) to estimate the 1-yr DBH increment (cm yr^{-1}) for individual trees in each plot, and compute their expected cumulative DBH change for the projection period prior to (i.e. positive DBH change), or past (i.e. negative DBH change) rotation age, by multiplying the predicted 1-yr DBH increment by the number of years before or after rotation age. We added the expected DBH change to the current DBH measurement of each tree to compute the DBH at rotation age 60 yr. Finally, for each measurement plot, we estimated the projected tree C stocks as the sum of individual tree C stocks based on projected, rotation-age DBH estimates, using the biomass equations described in Jenkins et al. (2003), and the species-specific C conversion factors by Birdsey (1992).

In order to estimate the total amount of sequestered C in tree biomass and harvested wood after two successive 30-yr rotations for pine and mixed stands, we assumed that 24 % of the C in harvestable tree biomass from the first rotation would remain sequestered in wood products in-use and in-landfills 30 yr after harvest (derived from Smith et al., 2006). The harvestable tree biomass included stem wood, stem bark, foliage, treetops, and branches. We assumed that stand management practices would remain the same during the second 30-yr rotation period ensuring similar tree growth and forest productivity within these stands. Therefore, the expected total amount of sequestered C in vegetation biomass (standing trees and wood products) in pine and mixed stands at the end of two consecutive 30-yr rotations was computed by adding the tree C content from the second rotation (including coarse roots), to the C amount stored in wood products in-use and in-landfills manufactured from harvested tree biomass from the first rotation.

Projected Litter Layer Biomass C and SOC in Natural Forest Stands

Litter layer biomass accumulation is a function of many environmental factors as well as tree species composition (Smith and Heath, 2002). Considering that the natural stands measured by Rodrigue (2001) grew under favorable climatic conditions characteristic of a typical temperate region of the U.S., and the fact that these natural stands were, on average, 55 yr of age and comprised primarily of mixed hardwood species, we assumed that the litter layer biomass and, hence, the litter C pool was in equilibrium (Smith and Heath, 2002). Also, due to a paucity of consistent information in the literature relative to changes in the SOC pool with time under tree vegetation cover, we assumed that the SOC pool in the natural sites had reached approximately steady state levels (Houghton and Hackler, 2000).

Projected Litter Layer Biomass C and SOC on Reforested Mined Land

For the mined plots, we assumed that SOC and litter C pools were not in equilibrium. We assumed that C sequestration in the SOC pool occurred at a constant rate until a new equilibrium was reached, similar to the assumptions made by Heath et al. (2002). We assumed that the annual SOC accumulation rate could be approximated by dividing the present SOC content (Mg C ha^{-1}) by stand age (yr) in each mined plot. We also assumed that the equilibrium state of SOC on mined sites could be approximated by the steady state SOC levels measured on adjacent, non-mined forest stands.

For pine and mixed forest stands, we assumed that C would continue to accumulate in the SOC pool without significant deviations from the assumed rates following timber harvest at age 30 yr, and immediate tree planting on the harvested sites (Johnson and Curtis, 2001). Therefore, we computed the amount of C sequestered in the soil during a 60-yr period (either one 60-yr rotation for hardwood stands; or two 30-yr rotations for pine and mixed stands) by either multiplying the stand-specific SOC accumulation rate by 60, or by assigning the equilibrium SOC content measured on the adjacent, non-mined land, whichever was smaller.

For all mined plots, we assumed that litter C would increase asymptotically until a steady state level was reached, and this accumulation could be modeled using established relationships between litter C and stand age. Smith and Heath (2002) modeled net accumulation of litter C as a function of age by forest type and region within the U.S. as follows:

$$\text{Litter layer C (Mg ha}^{-1}\text{)} = \frac{A * age}{(B + age)} \qquad \text{(Eq.3)}$$

where A = estimate of the upper limit of litter C in a mature forest; age = stand age; B = coefficient estimated by assuming that the model (i.e. the curve described by Eq.3) passes through an ecosystem-specific data point (or set of data points) for which both litter C and stand age are derived experimentally. For example, if the upper limit of litter C was represented by coefficient A', and the ecosystem-specific data point was (L', age'), where L' is the litter C measured at stand age age', then B could be computed as $(A{*}age'/L') - age'$.

We adopted the litter C decay equation developed by Smith and Heath (2002) to predict the amount of residual litter C at the end of the second 30-yr rotation (at age 60 yr) in pine and mixed stands following harvesting disturbance at age 30 yr:

$$\text{Residual litter layer C (Mg ha}^{-1}\text{) at age 60} = L * Exp\left(-\frac{30}{D}\right) \qquad \text{(Eq.4)}$$

where L = litter C accumulated under pine or mixed forest vegetation at the end of the first 30-yr rotation (estimated by substituting 30 for *age* in Eq.3); *Exp* = exponential function; *30* = number of years following the most recent harvest; D = litter layer biomass mean residence time (we used 8.4 yr for both pine and mixed stands) reported by Smith and Heath (2002, Table 4).

For each forest type (pine, hardwood, mixed), we developed mined-land specific coefficients A and B to substitute in Eq.3. Although defining the age when forest stands mature could be difficult (Smith and Heath, 2002), we designated it as the most likely point in time when a steady state of litter C stocks would be reached. Therefore, we assumed that, in general, hardwood, pine, and mixed stands would mature when they reached ages 70, 40, and 40 yr, respectively. We estimated coefficients A and B as follows:

$$A_i = \underset{i=1, j=1}{\overset{3, N}{Maximum}}\left(\frac{Litter\_C_{ij}}{Age_{ij}} * Mature\_age_i\right) \qquad \text{(Eq.5)}$$

$$B_{ij} = \left(\frac{A_i * Age_{ij}}{Litter\_C_{ij}} - Age_{ij}\right) \qquad \text{(Eq.6)}$$

where i (1 through 3) = forest type (pine, hardwood, mixed); j (1 through N) = number of plots of forest type i; A_i = maximum litter C in mature forests on mined land of forest type i; B_{ij} = litter layer accumulation coefficient for plot j of forest type i; $Litter\_C_{ij}$ = litter layer C stock (Mg ha^{-1}) measured on plot j of forest type i; Age_{ij} = stand age measured on plot j of forest type i; $Mature\_age_i$ = stand age of forest type i when trees mature.

For mined hardwood stands, we estimated litter C at the end of a 60-yr rotation by substituting 60, A_i (estimated in Eq.5), and B_{ij} (estimated in Eq.6) for *age, A,* and B parameters in Eq.3, respectively. For pine and mixed forest stands, we estimated litter C at the end of two successive 30-yr rotations by summing the litter C in the accumulating litter layer biomass, as a result of litter fall from regrowth during the second 30-yr rotation (Eq.3), and the litter C in the residual litter layer biomass, following harvesting at age 30 yr (Eq.4).

RESULTS

Ecosystem C Sequestration on Mined and Non-mined Forest Land

On average, the highest amount of ecosystem C on mined land was sequestered in pine stands (148 Mg ha^{-1}), followed by hardwood (130 Mg ha^{-1}) and mixed stands (118 Mg ha^{-1}) (Figure 1, Table 1).

More than three-quarters of ecosystem C on mined land was sequestered in the form of tree biomass (including above-ground biomass and coarse roots): 78, 82, and 77% in pine, hardwood, and mixed stands, respectively (Figure 1, Table 1). The distribution of the remaining one-quarter of ecosystem C among the SOC and litter C pools differed by forest type. Fourteen percent of ecosystem C in pine stands was located in the litter layer, and half that amount, 7%, was in the soil. In hardwood stands, the distribution of C between litter layer and soil was reversed, 14% was measured in the soil and 5% was in the litter layer. In mixed stands, the distribution was approximately equal (Figure 1, Table 1).

In the adjacent, non-mined study sites, one-third of ecosystem C content was found in the soil, 61% was in tree biomass, and 5% was in litter layer (Table 1). Non-mined hardwood stands contained 210 Mg C ha^{-1}, which was about 62% higher than the average of all mined stands (130 Mg C ha^{-1}). On average, the non-mined hardwood stands had approximately 42, 62, and 79% more cumulative C in tree biomass, litter layer, and soils, compared to mined pine, mined hardwood, and mined mixed forest stands, respectively (Table 1, Figure 1). The average rotation age ecosystem C in non-mined stands was 205 Mg ha^{-1}, which was about 34% greater than the average for all mined stands.

The response surface models presented in Figures 2 and 3 accounted for 39, 35, and 59% of the variation of ecosystem C across the spectrum of SI and Age in pine, hardwood, and mixed stands, respectively. Ecosystem C content in pine and mixed stands increased exponentially with the increase of SI, while it decreased with increasing stand age. In mined hardwood stands, ecosystem C increased asymptotically as stands aged across the range of SI, but SI had little or no effect on ecosystem C in these stands across the range of stand age (Figure 3). Although the distribution pattern of the individual mined hardwood stand data points suggested that SI could have some effect on the amount of ecosystem C, this effect was not statistically significant at the 95% probability level.

Rotation Age C Sequestration Empirical Models for Soil, Litter Layer, and Tree Biomass in Coniferous and Deciduous Forests on Mined Land

Across the range of SI, our mixed and pine stand models explained 34 and 52% of the variation of rotation-age ecosystem C content, respectively (Figure 4). In these stands, ecosystem C increased exponentially with increasing SI, so that for each 1 m SI increase, approximately 5 and 13 Mg C ha^{-1} more ecosystem C were sequestered during a 60-yr period under mixed and pine vegetation, respectively (Figure 4). Rotation-age ecosystem C in hardwood stands was not affected by changes in SI (Figure 4), which was also presented earlier in Figure 3. With an average estimate of 153 Mg C ha^{-1}, the rotation-age ecosystem C in hardwood stands was significantly lower than ecosystem C in pine stands on high quality sites, SI > 28 m (Figure 4). The differences of ecosystem C in pine and mixed stands were not statistically significant ($P>0.05$) across the spectrum of SI.

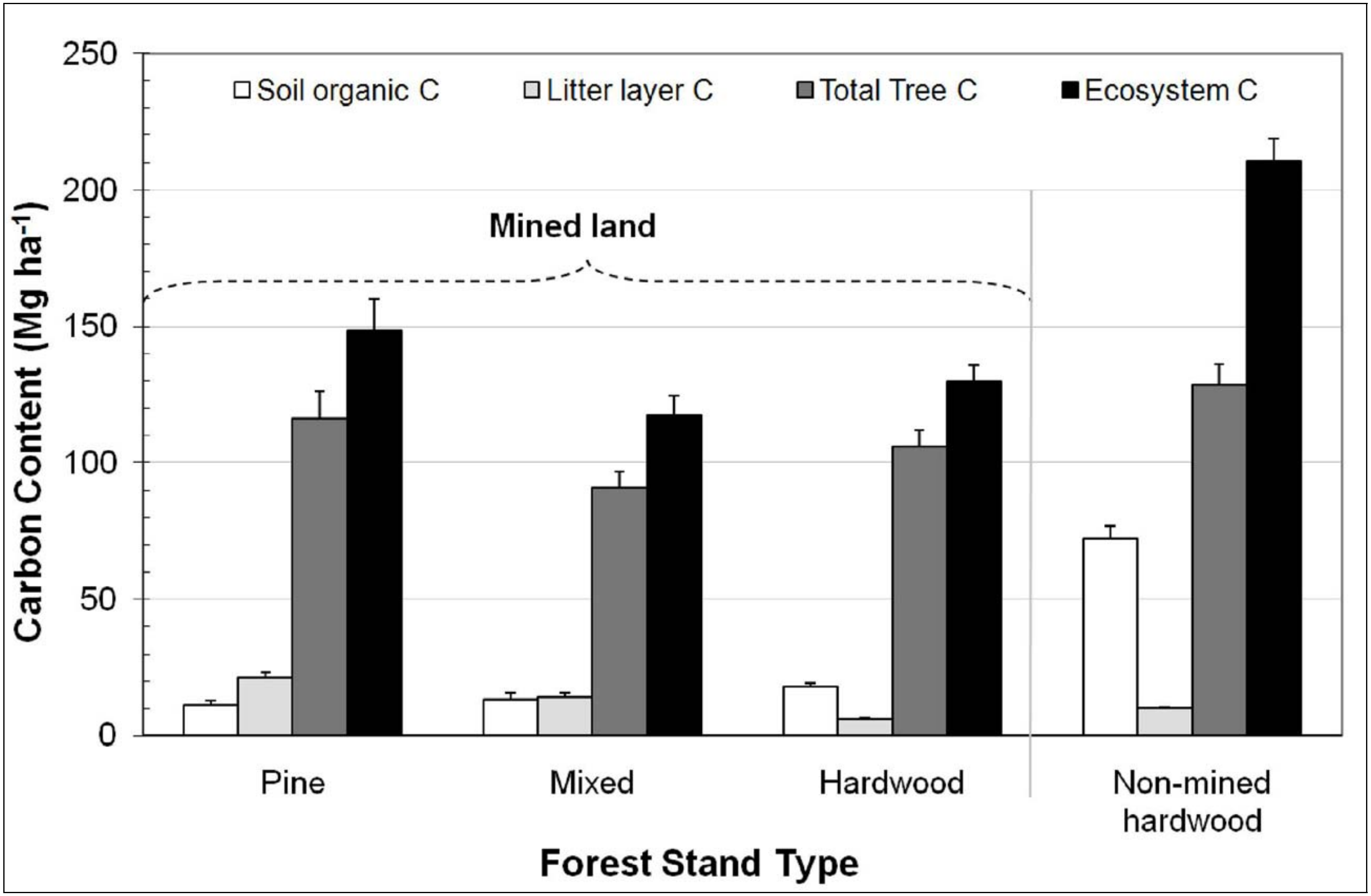

Figure 1. Average C stocks (by component) in forest ecosystems for three forest stand types on mined land (pine, mixed, hardwood), and adjacent, non-mined hardwood stands. Vertical lines represent one standard error of the mean estimate.

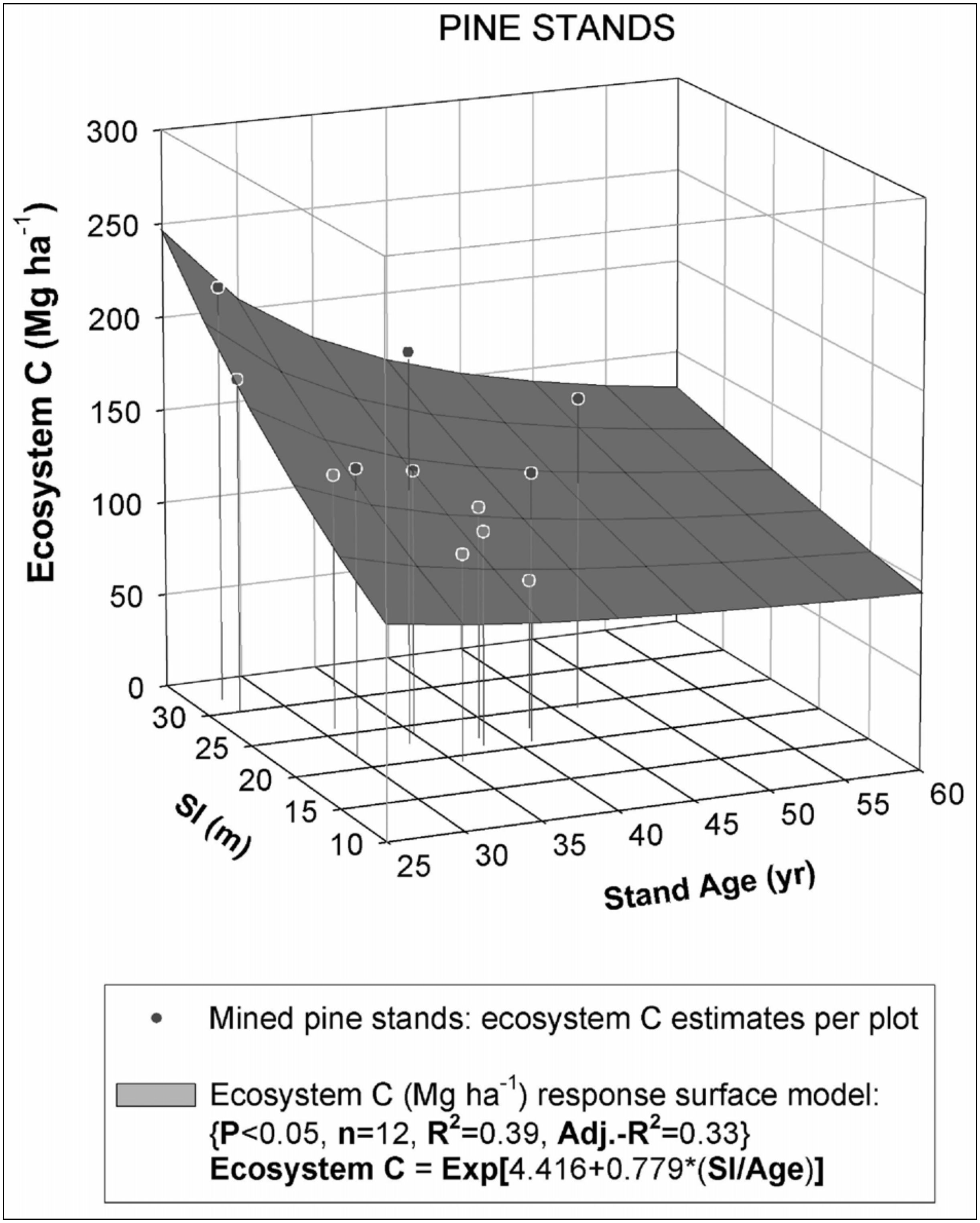

Figure 2. Ecosystem C content response surface by site index (SI) and stand age for pine stands on mined land in the Midwestern and Appalachian coal fields in the U.S. Site index is the height for white oak at base age 50 yr. Darker circles represent ecosystem C data points above the response surface, and lighter circles are those below it.

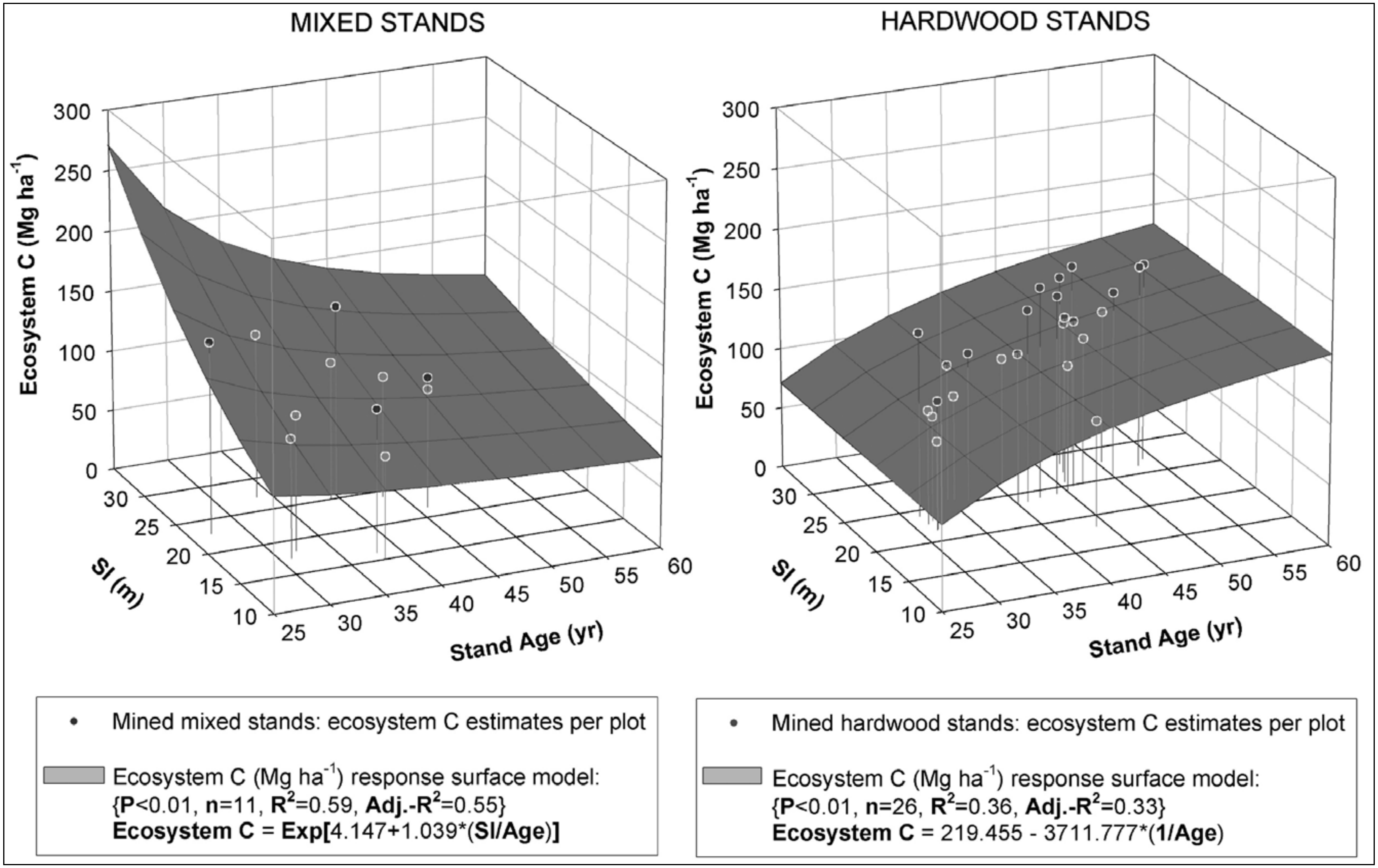

Figure 3. Ecosystem C content response surfaces by site index (SI) and stand age for mixed (left) and hardwood (right) stands on mined land in the Midwestern and Appalachian coalfields in the U.S. Site index is the height for white oak at base age 50 yr. Darker circles represent ecosystem C data points above the response surface, and lighter circles are those below it. One hardwood plot in OH (at age 71 yr) is not depicted on the graph for consistency between the two graphs; all data from OH were used in the analyses.

Table 1. Average ecosystem component C stocks (Mg ha^{-1}) at present stand age (yr), and projected to age 60 yr, in forest stands on mined and non-mined (adjacent) land. Shading indicates sites identified as outliers; average values were estimated without outliers. Coal-corrected SOC is reported for mined land along with the original Walkley-Black SOC estimates measured by Rodrigue (2001). Site index (SI) is the height (m) for white oak (WO) at base age 50 yr.

Stand type	State / Site	Age	SI	Total Tree C	Soil Organic C		Litter Layer C	Eco-system C	**Projected Ecosystem C, at 60 yr §**
					SOC	WB-SOC †			
					MINED LAND				
Pine	IN	47	24.5	118.2 (71) ‡	13.5 (8) ‡	35.8	35.1 (21) ‡	166.8	160.6
	KY	34	22.5	122.7 (78)	14.1 (9)	42.8	20 (13)	156.8	183.2
	PA	39	20.9	86.9 (78)	5.7 (5)	16.5	19.3 (17)	111.9	102.1
	VA	19	25.1	43.1	n/a	n/a	16.0	n/a	n/a
	WV 2	28	29.3	145.6 (81)	13.2 (7)	40.4	20.7 (12)	179.6	239.7
Average (mined pine)				***116.1 (78)***	***11 (7)***	***32.9***	***21.2 (14)***	***148.4***	***168.4***
Mixed	IN	45	22.4	77.3 (75)	12.6 (12)	36.9	13.1 (13)	103.0	103.1
	KY	38	25.9	108 (79)	21.3 (16)	57.6	7.1 (5)	136.4	156.9
	WV 1	35	16.7	80.6 (78)	5 (5)	15.6	18.3 (18)	103.9	108.7
	WV 2	27	22.9	118.1 (74)	21.6 (14)	70.7	19.1 (12)	158.8	227.6
Average (mined mixed)				***90.6 (77)***	***13 (11)***	***37.9***	***13.9 (12)***	***117.5***	***131.1***
Hardwood	IL	47	26.0	124.8 (85)	15.6 (11)	45.2	7.1 (5)	147.6	162.3
	IN	44	18.3	48.8 (55)	31.1 (35)	79.3	8.6 (10)	88.5	158.5
	KY	35	23.9	83.6 (79)	16.8 (16)	51.1	6 (6)	106.4	140.8
	OH	50	26.2	119.8 (83)	19.2 (13)	53.0	4.9 (3)	143.8	157.6
Average (mined hardwood)				***106.1 (82)***	***17.7 (14)***	***50.9***	***6.1 (5)***	***129.9***	***153.3***
					NON-MINED LAND (adjacent to mined sites)				
Hardwood	IL	43	27.9	156.3 (58)	108.1 (40)		6.9 (3)	271.3	282.7
	IN	47	24.7	113.1 (59)	73.5 (38)		5.4 (3)	192.1	198.8
	KY	52	23.8	101.7 (57)	66.3 (37)		11.5 (6)	179.5	196.2
	OH	59	23.3	97.3 (61)	53.3 (33)		8.9 (6)	159.5	160.9
	PA	61	25.6	148.1 (70)	48.3 (23)		14 (7)	210.4	208.8
	VA	71	27.3	148.3 (65)	66.5 (29)		15 (7)	229.8	222.4
	WV 1	62	25.5	131.9 (61)	72.8 (34)		10.3 (5)	215.1	213.3
	WV 2	51	25.9	136.8 (61)	81.3 (36)		8 (4)	226.0	231.9
Average (non-mined hardwood)				***128.6 (61)***	***72 (34)***		***9.9 (5)***	***210.5***	***205.4***

† WB-SOC, Walkley-Black estimate of soil organic C

‡ Numbers in parentheses (for total tree, soil, and litter layer C values) represent C distribution as percent of total ecosystem C. Sum of percent values may be different than 100 due to rounding.

§ Projected ecosystem C estimates at age 60 yr are the sum of projected tree, soil, and litter layer C pools (not presented in this table) as described in the text.

†† All three mined pine sites in VA, three of the six mined mixed sites in IN, and one of the four non-mined hardwood sites in PA were identified as outliers.

‡‡ n/a indicates not available.

In hardwood and mixed stands, there was a slight positive effect of SI on rotation-age tree C. The differences in tree C between hardwood and mixed stands were not statistically significant at the 95% probability level. Despite the steeper model curve depicting rotation-age tree C accumulation in pine stands (Figure 4), these estimates were not significantly different from rotation-age tree C in hardwood and mixed stands across the spectrum of SI (Figure 4).

The rotation-age litter C in pine stands was not affected by SI, while it decreased in hardwood and mixed stands as SI increased. The average rotation-age litter C in pine stands, 20 Mg C ha^{-1}, was significantly higher on high quality sites, SI>22 m, compared to hardwood and mixed stands (Figure 4).

In mixed and pine stands, rotation-age SOC increased with increasing SI, but the opposite was observed in hardwood stands. For each 1 m increase of SI, approximately 4 and 2 Mg C ha^{-1} more SOC were sequestered under mixed and pine vegetation, respectively, while 2 Mg C ha^{-1} less SOC was stored under hardwood vegetation (Figure 4).

Comparison of Rotation Age C Stocks on Mined and Non-mined Land

Presented in Figure 5 is an overlay of the rotation-age ecosystem C, tree C, litter C, and SOC models and data for hardwood stands established both on mined and adjacent, non-mined lands. The mined hardwood C models were presented earlier in Figure 4, but were used again in Figure 5 for better visualization and comparison between the results for mined and non-mined land.

The rotation-age ecosystem C model for non-mined hardwood stands ($R^2 = 0.44$) indicated an asymptotic increase of rotation-age ecosystem C in these stands with the increase of SI (Figure 5). At rotation age, non-mined ecosystem C was significantly greater than mined ecosystem C for high quality sites, SI > 22 m, and was not statistically different for low quality sites. In general, the differences in rotation-age ecosystem C on mined and non-mined stands were largely due to differences in the respective SOC pools. On high quality sites, non-mined hardwood stands sequestered significantly higher SOC than mined hardwood stands. At rotation age, for each 1 m increase of SI, approximately 3 Mg C ha^{-1} more SOC was sequestered in non-mined hardwood stands, while the SOC pool decreased with increasing SI in mined hardwood stands (Figure 5).

Rotation-age tree C stocks in mined and non-mined hardwood forests were similar across the spectrum of SI (Figure 5). In non-mined stands, rotation-age litter C was not affected by changes in SI, averaging 10 Mg C ha^{-1}. On high quality sites, rotation-age litter C in non-mined stands was significantly ($P<0.05$) higher compared to the mined hardwood stands.

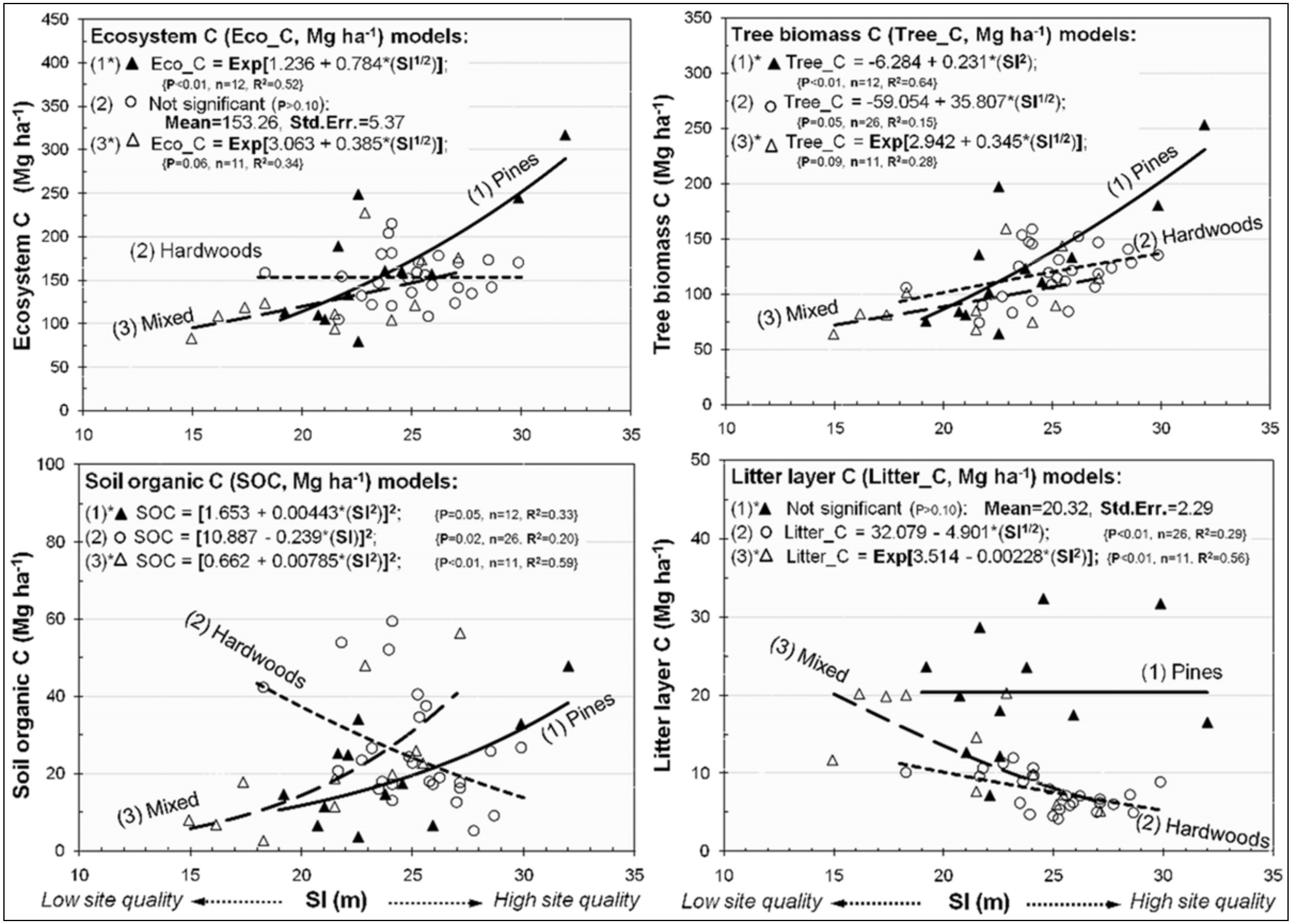

Figure 4. Regression models for total ecosystem, tree, soil, and litter layer C content projected to rotation age 60 yr on forested mined land for three forest types, pine, mixed, hardwood, in the Midwestern and Appalachian coal fields in the U.S. Models followed by * were developed without data outliers as described in the text. Site index (SI) is the height for white oak (WO) at base age 50 yr.

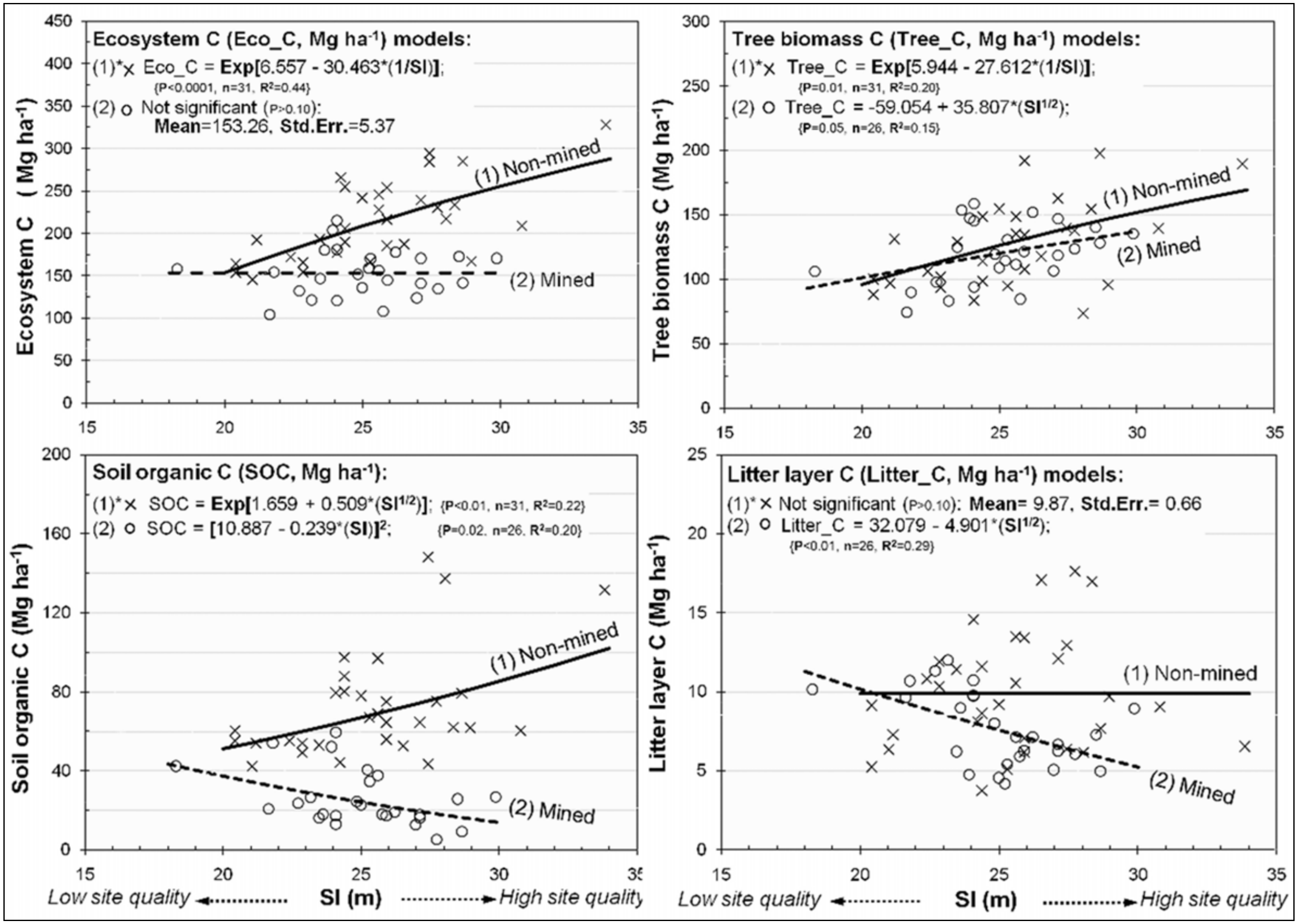

Figure 5. Comparison of regression models for total ecosystem, tree, soil, and litter layer C content projected to rotation age 60 yr in hardwood stands on mined and non-mined land in the Midwestern and Appalachian coal fields in the U.S. Models followed by * were developed without data outliers as described in the text. Site index (SI) is the height for white oak (WO) at base age 50 yr. The mined hardwood stand models were also depicted in Figure 4.

DISCUSSION

Ecosystem C Sequestration on Mined and Non-mined Forest Land

Little has been done to quantify the C pools associated with tree biomass of mature, planted forests on mined sites (Burger et al., 2003). The results from this study provided the necessary information to bridge this knowledge gap. Overall, our mined study sites were new forest communities that, in some cases, accumulated nearly as much C in the tree biomass as that sequestered in trees on adjacent non-mined sites (Table 1). Most of these new forests contained valuable species and trees were well spaced (Rodrigue et al., 2002). Our data also showed that some low-quality sites can be more productive after mining with the potential to develop greater amounts of tree C per unit area, especially for forest stands that are under-stocked, or high-graded, both of which are commonly found in the eastern U.S.

Our tree C estimates were comparable to other forests in the East. Kaczmarek et al. (1995) reported between 61 and 117 Mg C ha^{-1} in tree biomass of hardwood forests in Indiana. For all but four non-mined and mined hardwood plots in Indiana and western Kentucky, our estimates were well within their C estimates. Richter et al. (1995) found 140.6 Mg C ha^{-1} in the tree biomass of a 35-yr-old loblolly pine site in South Carolina. Within our study, seven sites in KY contained loblolly pine. The tree C content on these plots ranged from 99 to 170 Mg ha^{-1} at stand ages ranging from 30 to 38 yr.

Our litter C estimates also compared favorably with other studies in the eastern U.S. which reported litter C estimates ranging from 4 to 14.4 Mg C ha^{-1} depending on age and forest species (Hoover et al., 2000). Sites with a higher conifer component tended to develop greater C pools within the litter layer (Vimmerstedt et al., 1989). On a 35-yr-old loblolly pine site in the Piedmont of South Carolina, litter layer C averaged 32.8 Mg C ha^{-1} (Richter et al., 1995).The litter C on our loblolly pine plots in western Kentucky, with stand age ranging from 30 to 35, averaged 24 Mg C ha^{-1}. Because of the different chemical composition of the foliage in pine stands, particularly the higher lignin and wax content, different leaf structure, and more acidic conditions, compared to the foliage under hardwood tree canopy, litter layers in our pine stands tended to accumulate, probably due to slower rates of decomposition (Smith and Heath, 2002).

Our mined site coal-corrected SOC estimates were lower than the SOC pools reported in other investigations on mined land (Table 1). Akala and Lal (1999) reported that 30-yr-old reforested mined sites (to 0.5 m depth) contained 51.5 Mg ha^{-1}of SOC, and 50-yr-old sites contained 54.9 Mg C ha^{-1}; all measurements were done by the WB procedure. However, results from other studies on mined land also indicated that the WB method could over-estimate SOC due to interference from coal particles in the soil (Daniels and Amos, 1982; Amichev, 2007). Mined sites approximately 30-yr-old in our study contained 16 Mg C ha^{-1}, while approximately 50-yr-old mined sites contained an average of 17 Mg C ha^{-1}.

Average non-mined-site SOC levels were similar to estimates reported in the literature for temperate forests. Post et al. (1982) estimated SOC to 1 m depth at 79 and 60 Mg ha^{-1} for dry and moist warm temperate forests, respectively. Researchers in the eastern U.S. reported SOC levels for depths from 0.5 m to bedrock ranging between 36 and 130 Mg ha^{-1} (Kaczmarek et al., 1995; Hoover et al., 2000).

Unlike the tree C and litter C pools, SOC content in mine soils was consistently lower than the non-mined SOC stocks (Table 1). Therefore, of the three ecosystem components, the soil had the greatest potential for sequestering and storing additional C. Mine soils might be regarded as ‘empty cups’ that have the capacity to accumulate and store large amounts of sequestered C compared to undisturbed soils. Assuming that hardwood forest would be the long-term (decades) land use practice following mining and reclamation, the current SOC levels of a mined site would increase considerably until they reach the approximate SOC levels in natural hardwood forests. For example, mine soils under hardwood vegetation have the potential to store 307% more SOC, resulting in more than a three-fold increase from 18 (mined hardwood stands) to 72 Mg C ha^{-1} (non-mined hardwood stands)(Table 1). On average, the SOC content in mine soils could reach the approximate SOC levels in adjacent natural forests in 350 yr, ranging from 160 (KY) to 760 yr (WV 1), assuming that the current SOC sequestration rates, estimated as (current mined site SOC stock) / (stand age), would remain unchanged. . These estimates were higher than values for forested mined land reclaimed with topsoil application. Akala and Lal (2001) reported that SOC equilibrium could be attained between 110 and 150 yr following forest establishment in Ohio. However, all above estimates could be affected by mine site quality, reclamation method, climate, forest type, stand age, and previous land use.

The ecosystem C response surface models developed in this study revealed a decreasing trend of ecosystem C with increasing stand age in mined pine and mixed stands. (Figures 2 and 3). In general, these findings followed our observations that forest stands with a high, planted loblolly or pitch pine component began to collapse and be replaced with native hardwoods beginning at approximately age 30. That is, the C content in large dead pine trees (i.e. standing dead trunks, dead coarse roots, and dead woody material lying on the forest floor) was transferred to the woody debris C pool, which, on average, could range from 10 to 14 Mg ha^{-1} in forests of the eastern U.S., and represent between 14 and 24% of the C in tree biomass, including coarse roots (Turner et al.,1995). As native hardwoods continue to grow and replace the aging pine trees in older (> 30 yr) mined pine and mixed stands, we expect ecosystem C to level off and begin increasing again following a new trend – that of a hardwood forest, similar to the ecosystem C response surface presented in Figure 3. The ecosystem C in hardwood stands increased until a maximum was reached which was as expected. Similar models with asymptotic leveling off of biomass yield with increasing stand age are widely-used to describe tree growth in natural, even-aged stands (Avery and Burkhart, 1994a).

Rotation Age C Sequestration Empirical Models as a Function of SI for Soil, Litter Layer, and Tree Biomass in Coniferous and Deciduous Forests on Mined Land

Projecting individual C pools from their current to the expected (future or past) levels at rotation age 60 yr standardized our data with respect to stand age. Carbon pool projections in our study sites were positive (when projected into the future) or negative (when projected into the past). The average positive ecosystem C projections in pine, mixed, and hardwood stands on mined land were an increase of 18, 15, and 22%, while the average negative projections were a decrease of 12, 5, and 7% of the current ecosystem C values, respectively. For all forest types, positive ecosystem C projections were mainly driven by a positive projection in the SOC pool, an average increase of 74, 64, and 47% of the current SOC values in pine, mixed, and hardwood stands, respectively, and less so from positive projections in the tree C and litter C pools (<30%). In comparison, negative ecosystem C projections were not driven by a single ecosystem component, but were the cumulative result of the projections in all components. In our non-mined hardwood forests, positive and negative ecosystem C projections were less than 6% of current values, on average, and were driven only by projections made in the tree C pool (<10% of current values); current SOC and litter C pools were assumed to be in equilibrium states.

Similar to the ecosystem C response surface model presented in Figure 3, the rotation-age ecosystem C model for mined hardwood stands also showed a negligible response to increasing SI (Figure 4). However, the latter appeared more reasonable after analyzing the individual C pools in these stands. At the current young stage of mine soil development, soil conditions on high quality sites are more favorable for a myriad of soil micro- and macro-organisms (Showalter et al., 2007), which decompose the organic matter in the litter layer and soil to CO_2 at relatively higher rates, compared to low quality sites. As a result, we believe that the higher amount of sequestered C in tree biomass, tree roots, litter layer, and soil on high quality sites is offset by higher microbial respiration, compared to low quality sites. This would explain the decreasing trends of rotation-age litter C and SOC pools with increasing SI in mined hardwood stands, which canceled out the increasing trend of rotation-age tree C. As a result, the total ecosystem C content in hardwood stands remained unchanged across the spectrum of SI (Figure 4).

From a C sequestration perspective, the establishment of pine forests on mined land, compared to pure hardwood stands, would result in up to 85% more ecosystem C sequestered in these ecosystems over 60 years where pine and mixed stands were more sensitive to site quality gradients compared to hardwood stands. Mixed stands may provide additional ecosystem services such as wildlife habitat and aesthetic value, although from a silvicultural point of view, native pines are better grown as monocultures.

Comparison of Sequestered C on Mined and Non-mined Land

Our results from the comparison between mined and non-mined land corroborate the observations of other mined land researchers. In particular, there is evidence that post-mining productivity can be greater on originally poor sites (SI < 20 m), but post-mining productivity is lower on medium to high quality sites (Burger et al., 2003). The increasing disparity between rotation-age ecosystem C on mined and non-mined sites with increasing SI was due to the greater amount of SOC in non-mined forests compared to the mined hardwood stands (Figure 5). The tree C and litter C pools were relatively unaffected by the mining practices, and hardwood tree growth and litter layer accumulation rates were restored to pre-mining levels.

Over time, the mine soil SOC pool will increase and will eventually attain a new equilibrium level probably similar to that of the soils in adjacent, non-mined sites. This is the ‘empty cup’ for C storage representing the important distinction between forest ecosystems on mined and non-mined land. The amount of additional SOC that could be sequestered in forested mine soils could be between 25 to 100 Mg C ha^{-1}, depending on site quality (Figure 5).

CONCLUSIONS

The development of productive forests on reclaimed land fulfills the requirements of the Surface Mining Control and Reclamation Act of 1977, which mandates the return or enhancement of pre-mining productivity levels. Restoring forests to their original level of productivity would also establish a long-term sink for atmospheric CO_2. Considering that very little organic C is present on recently reclaimed mined sites, there is great potential for sequestering C by restoring forest sites to a level of productivity equal to, or greater than that present before mining. Unlike undisturbed soils, mine soils without topsoil can be regarded as an 'empty cup' with a capacity to sequester and store significant amounts of atmospheric CO_2.

This study characterized the C pools associated with mature, planted forests on mined sites, and provided a better understanding of the C dynamics in these ecosystems. Overall, mined sites accumulated nearly as much C in the tree and litter layer biomass as that sequestered in trees on adjacent, non-mined sites. Unlike the tree and litter C pools, however, SOC stocks were consistently lower on mined sites, providing a unique opportunity to sequester and store additional C on mined land. Our analyses indicated that the amount of additional SOC that could be sequestered in forested mine soils could be between 25 to 100 Mg C ha^{-1}, depending on site quality. However, it could take a long period of time (>60 yr) for these SOC additions to occur due to the nature of mined land reclamation. During coal mining, and the following mined land reclamation process (earth removal, storage, mixing, transportation, and compaction), native topsoil containing seed pools and microbial communities in the soil are usually buried or destroyed. As a consequence, the natural cycle of terrestrial C is severely interrupted. The addition of native topsoil containing seed pools and microbial communities could help restore this natural cycle and narrow the disparity between pre- and post-mining SOC levels. Therefore, we recommend reclamation methods that introduce, accumulate, and stabilize soil organic matter, re-establish soil microbial communities in mine soils, and prepare mined sites in ways that maximize the growth of planted trees and the recruitment of other native plants.

The results from this research extend further our knowledge about C sequestration on mined land. The empirical C models for soil, tree, and litter layer biomass developed in this study could be used as building components of a decision support system (DSS) for predicting C stocks and fluxes for multiple rotations and varying rotation lengths and for different forest types. The greater good of such a DSS would be the ability to make informed decisions about reclamation methods and the types of forests to establish on mined lands that would maximize the C sequestration potential of the land, and be most beneficial to landowners and society as a whole.

ACKNOWLEDGEMENTS

We would like to thank the Powell River Project, the U.S. Department of Energy (DE-PS26-02NT41422), and the Office of Surface Mining for financial support of this study. Special thanks go to those people involved in the location of study sites, including C. Ashby, A. Boyer, F. Brenner, D. Burger, B. Gray, R. Gullic, T. Probert, J. Skousen, J. Vimmerstedt, and D. Williamson; and to our colleagues at Virginia Tech, K. Hollandsworth, R. Oderwald, S. Zedaker, and C. Zipper, for their technical assistance.

REFERENCES

Akala, V.A., Lal, R., 1999. Mineland reclamation and soil organic carbon sequestration in Ohio. In: Mining and Reclamation for the Next Millennium. Vol.1. Proceedings, American Society of Surface Mining and Reclamation. Annual National Meeting, Aug. 13-19, 1999, Scottsdale, AZ., pp. 322-329.

Akala, V.A., Lal, R., 2001. Soil organic carbon pools and sequestration rates in reclaimed minesoils in Ohio. Journal of Environmental Quality 30, 2098-2104.

Amichev, B.Y., 2007. Biogeochemistry of Carbon on Disturbed Forest Landscapes. Ph. D. Dissertation. University Libraries, Virginia Polytechnic Institute and State University, Department of Forestry, Blacksburg, VA, p. 371.

Avery, T.E., Burkhart, H.E., 1994a. Growth and Yield Models, Ch. 16. In: Duffy, A., Morriss, J.M. (Eds.), Forest Measurements. Published by McGraw-Hill.

Avery, T.E., Burkhart, H.E., 1994b. Site, stocking, and stand density, Ch. 14. In: Duffy, A., Morriss, J.M. (Eds.), Forest Measurements. Published by McGraw-Hill.

Birdsey, R.A., 1992. Carbon storage and accumulation in the United States forest ecosystems. USDA Forest Service General Technical Report. WO-59, 51 pp.

Brender, E.V., Clutter., J.L., 1970. Yield of even-aged, natural stands of loblolly pine. Georgia Forest Research Council, Report No. 23.

Burger, J.A., Auch, W.E., Oderwald, R.G., Eisenbies, M., 2003. White pine growth and yield on a mined site in Virginia: Response to thinning and pruning. In: Barnhisel, R.I. (Ed.), Working Together for Innovative Reclamation, 20th National Conference of the American Society of Mining and Reclamation. June 3-6, 2003. Billings, MT., pp. 226-240.

Burger, J.A., Powers, R.F., 1991. Field designs for testing hypotheses in long-term site productivity studies. In: Dyck, W.J., Mees, C.A. (Eds.), Long-term field trials to assess environmental impacts of harvesting. IEA/BE T6/A6 Report No. 5. . Forest Research Institute, FRI Bulletin No. 161., Rotorua, New Zealand, pp. 79-105.

Burger, J.A., Zipper, C.E., 2002. How to Restore Forests on Surface-mined Land. [Available Online] (Verified December 12, 2007), http://www.ext.vt.edu/pubs/mines/460-123/460-123.pdf, Virginia Cooperative Extension, Publication Number 460-123.

Carmean, W.H., Hahn, J.T., Jacobs, R.D., 1989. Site index curves for forest tree species in the eastern United States. USDA Forest Service, North Central Forest Experimental Station, General Technical Report, NC-128, 142pp.

Daniels, W.L., Amos, D.F., 1982. Chemical characteristics of some southwest Virginia minesoils. In: Graves, G.H. (Ed.), Proceedings, Symposium on Surface Mining, Sedimentology, and Reclamation. Office of Engineering Serv., College of Engineering, Univ. of Kentucky, Dec 6-10, 1982, Lexington, KY.

Doolittle, W.T., 1958. Site index comparisons for several forest species in the southern Appalachians. Soil Science Society of America Proceedings 22, 455-458.

Heath, L.S., Birdsey, R.A., Williams, D.W., 2002. Methodology for estimating soil carbon for the forest carbon budget model of the United States, 2001. Environmental Pollution 116, 373-380.

Hoover, C.M., Birdsey, R.A., Heath, L.S., Stout, S.L., 2000. How to Estimate Carbon Sequestration on Small Forest Tracts. Journal of Forestry 98, 13-19.

Houghton, R.A., Hackler, J.L., 2000. Changes in terrestrial carbon storage in the United States. 1: The roles of agriculture and forestry. Global Ecology and Biogeography 9, 125-144.

Intergovernmental Panel on Climate Change (IPCC), 2000. Land use, land-use change, and forestry (Including Summary for Policymakers). A Special Report of the IPCC.

Jackson, R.B., Mooney, H.A., Schulze, E.D., 1997. A global budget for fine root biomass, surface area, and nutrient contents. Proceedings of the National Academy of Sciences 94, 7362-7366.

Jenkins, J.C., Chojnacky, D.C., Heath, L.S., Birdsey, R.A., 2003. National-scale biomass estimators for United States tree species. Forest Science 49, 12-35.

Johnson, D.W., Curtis, P.S., 2001. Effects of forest management on soil C and N storage: meta analysis. Forest Ecology and Management 140, 227-238.

Kaczmarek, D.J., Rodkey, K.S., Reber, R.T., Pope, P.E., F. Ponder Jr., 1995. Carbon and nitrogen pools in oak-hickory forests of varying productivity. In: Gottschalk, K.W., Fosbroke, S.L.C. (Eds.), 10th Central Hardwood Forest Conf., USDA Forest Service General Technical Report, NE-197. Northeast Experimental Station, Radnor, PA, March 5-8, Morgantown, WV, pp. 79-93.

Nelson, D.W., Sommers, L.E., 1982. Total carbon, organic carbon, and organic matter. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties. ASA-SSSA, Madison, WI, pp. 539-579.

Nelson, T.C., Lotti, T., Brender, E.V., Trousdell., K.B., 1961. Merchantable cubic-foot volume growth in natural loblolly pine stands. USDA Forest Service, Southern Forest Experiment Station, Asheville, NC. Station paper No. 127. .

Nyland, R.D., 1996. SILVICULTURE: Concepts and Applications. Published by McGraw-Hill.

Post, W.M., Emanuel, W.R., Zinke, P.J., Stangenberger, A.G., 1982. Soil carbon pools and world life zones. Nature 298, 156-159.

Richter, D.D., Markewitz, D., Dunsomb, J.K., Heine, P.R., Wells, C.G., Stuanes, A., Allen, H.L., Urrego, B., Harrison, K., Bonani., G., 1995. Carbon cycling in a loblolly pine forest: implications for the missing carbon sink and for the concept of soil, Ch.11. In: McFee, W.W., Kelly, J.M. (Eds.), Carbon Forms and Functions in Forest Soils. Soil Science Society of America, Madison, WI, pp. 233-251.

Robertson, P.G., 1987. Geostatistics in Ecology: Interpolating With Known Variance. Ecology 68, 744-748.

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. University Libraries, Virginia Polytechnic Institute and State University, Blacksburg, VA. , p. 299.

Rodrigue, J.A., Burger, J.A., 2004. Forest soil productivity of mined land in the midwestern and eastern coalfield regions. Soil Science Society of America Journal 68, 833-844.

Rodrigue, J.A., Burger, J.A., Oderwald, R.G., 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.

SAS, 2007. SAS software, Version 9.1.3 Service Pack 2: SAS Documentation. SAS Institute Inc., Cary, NC, USA.

Showalter, J.M., Burger, J.A., Zipper, C.E., Galbraith, J.M., Donovan, P.F., 2007. Influence of mine soil properties on white oak seedling growth: A proposed mine soil classification model. Northern Journal of Applied Forestry (In Press).

Skog, K., Nicholson, G., 1998. Carbon cycling through wood products: the role of wood and paper products in carbon sequestration. Forest Products Journal 48, 75-83.

Smith, J.E., Heath, L.S., 2002. A model of forest floor carbon mass for United States forest types. USDA Forest Service, Northeastern Research Station, Research Paper NE-722. Newtown Square, PA.

Smith, J.E., Heath, L.S., Skog, K.E., Birdsey, R.A., 2006. Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. USDA Forest Service, Northeastern Research Station, General Technical Report NE-343. Newtown Square, PA.

Turner, D.P., Koerper, G.J., Harmon, M.E., Lee, J.J., 1995. A carbon budget for forests of the conterminous United States. Ecological Applications 5, 421-436.

U. S. Office of Surface Mining (OSM), 2007. State and Indian Regulatory Program Permitting: 1997-2004. [Available online] (Verified March 23, 2007), http://www.osmre.gov/statisti.htm.

United Nations, 1998. Kyoto Protocol to The United Nations Framework Convention on Climate Change. [Available online] (Verified January 10, 2007), http://unfccc.int, Kyoto, Japan.

Vimmerstedt, J.P., House, M.C., Larson, M.M., Kasile, J.D., Bishop, B.L., 1989. Nitrogen and Carbon accretion on Ohio coal minesoils: Influence of soil-forming factors. Landscape and Urban Planning 17, 99-111.

Vitousek, P.M., Mooney, H.A., Lubchenco, J., Melillo, J.M., 1997. Human domination of Earth’s ecosystems. Science 277, 494-499.

Wenger, K.F., 1984. Forestry Handbook. 2nd ed. John Wiley & Sons, New York, NY.

Wright, J.A., DiNicola, A., Gaitan, E., 2000. Latin American forest plantations: opportunities for carbon sequestration, economic development, and financial returns. Journal of Forestry 98, 20-23.