CARBON SEQUESTRATION BY FORESTS AND SOILS ON MINED LAND IN THE MIDWESTERN AND APPALACHIAN COALFIELDS: PRELIMINARY RESULTS[1]

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Abstract. Reforestation of mined land has the potential to sequester large amounts of atmospheric carbon on sites where carbon-based fuels were extracted. The extent to which reforested mined land captures atmospheric carbon compared to natural undisturbed land is still largely unknown. We compared the amount of carbon sequestered on 14 pre-SMCRA reforested mined sites to 8 adjacent natural sites in the midwestern and eastern coalfields. Rates of carbon sequestration ranged from 0.7 to 6.7 Mg ha^{-1} yr^{-1}, depending on mine soil quality. After 20 to 55 yr, total site carbon levels on mined study sites averaged 161 (± 24) Mg ha^{-1} (hardwood stands) and 148 (± 41) Mg ha^{-1} (pine stands), while total carbon amounts on natural sites averaged 207 (± 36) Mg ha^{-1}. The amount of carbon captured across mined sites was largely a function of forest stand age and forest and site productivity, quantitatively expressed as site index (SI) of white oak at base age 50 years. Ecosystem carbon prediction models on natural and mined sites were generated for a wide spectrum of SI and age, including carbon sequestered in tree biomass, litter layer, and soil. The natural sites' multivariate regression model (P=0.002) explained about 68% of the total variation among natural sites and the mined sites' model (P=0.064) explained 28% of the total variation in measured carbon among mined sites. This study showed that current reclamation procedures and techniques restore carbon sequestration potential on low quality sites, but carbon sequestration potential is degraded on medium to high quality sites. Better reclamation techniques are needed to ensure long-term restoration of the potential of forests and forest soil systems to sequester carbon at pre-mining levels for the entire spectrum of SI and stand age.

Additional Key words: reclamation, reforestation, forest soils, carbon prediction models.

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Introduction

Under the 1992 Framework Convention on Climate Change, 153 nations agreed to mitigate global climate change by controlling greenhouse gases. The governments and industries of these nations would reduce greenhouse gasses by sequestering atmospheric carbon or by reducing CO_2 emissions (Wright et al., 2000).

Carbon accreditation of forest development projects is one approach to sequestering atmospheric carbon under the climate change agreement. Forests provide a low-cost method of carbon accreditation compatible with other environmental, economic, and social development projects (Wright et al., 2000). Forest development projects use trees to sequester carbon for long-term storage. As young forests develop, atmospheric carbon is locked into wood during growth and stored in litter layers. However, some workers identify sequestration of carbon in tree biomass and litter as a delaying tactic that only buys time for finding more efficient solutions of C sequestration (IPCC, 2000).

Carbon is also incorporated into the soil via root turnover, litter decomposition, and turnover of meso- and microfauna. The carbon sequestration potential of a forest depends on stand growth rates, the site's biological carrying capacity, stand age, and product utilization. Furthermore, carbon sequestration and storage may be increased if forests are harvested and trees are converted into wood products (Skog and Nicholson, 1998).

The eastern deciduous hardwood forest of the midwestern and eastern regions of the United States stores large amounts of carbon in forest biomass and forest soils. Anderson (1991) estimated average worldwide carbon levels for temperate deciduous forests at 175 Mg ha^{-1}, with 90 Mg ha^{-1} in the plant biomass and 85 Mg ha^{-1} in the soil and litter layer. The average carbon content of forests in the eastern half of the U.S. was 179 Mg ha^{-1}, including 81 in the forest biomass, 9 Mg ha^{-1} in the litter layer, and 89 Mg ha^{-1} in the soil (derived from Turner et al., 1995). These studies provide baseline examples of carbon content in temperate deciduous forests, and they show that carbon content between ecosystem components can vary by forest-specific conditions.

Within the eastern and central hardwood regions, thousands of acres have been surface-mined for coal. Coal mining and the use of the mined coal for power generation are major sources of 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 typically bulldozed in piles and burned.

A compelling argument can be made for restoring forestlands mined for coal to carbon-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. Maximizing the productivity of the restored forest is also compelling. Productive forests will enhance the site's ability to recapture the carbon contained in the original forest and some of the carbon contained in the coal that was mined beneath it.

The carbon sequestration potential of forested mined land is not well known. It must be characterized in order to make comparisons with other carbon sequestration projects, and to better understand differences in carbon capture levels under varying forest and mined land conditions. Therefore, we characterized fourteen 20- to 55-year-old mined sites throughout the midwestern and eastern coal regions to accomplish the following objectives: (1) quantify the tree, litter, and soil carbon sequestered as a function of forest and site age and quality, and (2) compare the carbon sequestered on these sites to adjacent natural forested sites.

Methods

Study Approach, Site Selection and Layout

This study was designed using the classic retrospective research approach of evaluating long-term response of forests to treatments imposed at an earlier time (Powers et al., 1994). Retrospective studies look back in time to assess the effects of past treatments or conditions in the present. The principal advantage of retrospective studies is expediency in weighing the long-term effect of earlier events. The main disadvantage is the uncertainty associated with the precise conditions that existed when the treatments were imposed. Because the investigator usually has nothing to do with the application of the treatments, pre-treatment characterization data may not be available; pre-treatment conditions must be established from historical records. Nonetheless, retrospective studies provide an indispensable and powerful way of studying long-term phenomena such as forest growth and development (Burger and Powers, 1991).

Fourteen pre-SMCRA forest sites across seven states, each with an average size of 2.5 ha of contiguous forest cover, were located on mined lands in the midwestern and eastern coal fields of the U.S. (Fig. 1). The location and site types included in this study were chosen to represent the mining and reclamation conditions that existed in the midwestern and eastern coalfields prior to the passage of SMCRA in 1977. After visual examination of all potential locations, sites for measurement were chosen based on adequate stand size, stand age (indicating pre-SMCRA planting), forest conditions present, and the presence of an adjacent, suitable, and comparable non-mined forested site (Rodrigue, 2001). The 14 sites ranged from 20 to 55 years old. The canopy layer species ranged from pure hardwood and conifer stands to mixed stands (Table 1). All sites were planted with trees produced in local nurseries. Soils on the mined sites were classified as Udorthents (Sencindiver and Ammons, 2000; Zeleznik and Skousen, 1996).

Adjacent to the mined sites, reference native forest sites were located and measured. The non-mined sites were chosen based on the same criteria as the mined sites. With assistance from local experts and with the use of stand and soil maps we located forest stands on natural, undisturbed soils that best represented the local forest and soil types (Rodrigue, 2001). The selected non-mined sites represented land, soil and forest conditions similar to those present on mined sites before they were disturbed. All non-mined sites were mature, well-stocked, native forest stands. Natural soils included Inceptisols, Ultisols, and Alfisols.

A 20 x 20-m grid was superimposed across the site after the boundaries were established. A 20-m buffer strip was maintained on all edges of each forest site (Fig. 2). Grid lines were placed perpendicular to the banks of open-pit mined sites where more than one spoil bank existed to ensure that the site's microtopography was taken into account. All subsequent sampling was based from intersections of the grid. Field data collection took place between May and August 1999, with the exception of two sites, which were measured in August 1998.

Site Carbon Capture Calculations

Carbon captured in tree biomass, including biomass in the above-ground and coarse-root components, was estimated on each site by randomly choosing measurement points at four of the 20 x 20-m grid intersections (Fig. 2). Trees in the main canopy greater than 13.0 cm in diameter at breast height (dbh) were tallied within a 404 m^2 circular plot.

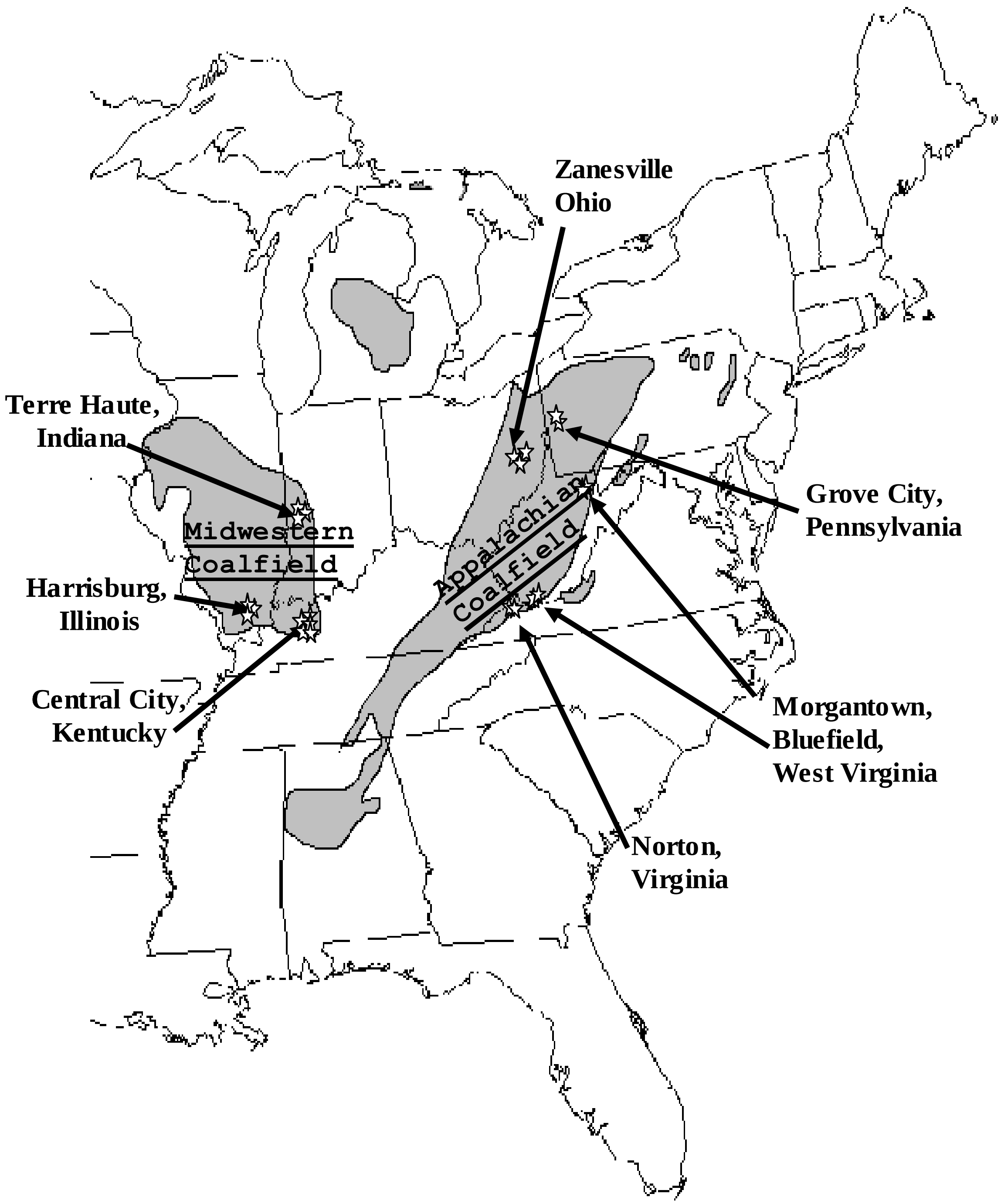

Figure 1: General location of study sites in the Midwestern and Appalachian coalfields.

Table 1. General description of 8 non-mined (natural) and 14 mined sites in the Midwestern and Appalachian coalfields, including dominant canopy species and stand age at time of measurement. State abbreviations denote the specific location of each site. Additional site species-specific information is in Rodrigue (2001).

State	Site	History	Canopy Type	Stand Age
Illinois	***IL-C***	*Natural*	*Scarlet oak/red maple*	***43 †***
	IL-1	Mined	White oak/tulip poplar	54
	IL-2	Mined	Cottonwood	43
Indiana	***IN-C***	*Natural*	*Oak/tulip poplar*	***40 †***
	IN-1	Mined	Mixed hardwoods/Pitch pine	55
	IN-2	Mined	Pitch pine	50
Kentucky	***KY-C***	*Natural*	*Oak/tulip poplar*	***52 †***
	KY-1	Mined	Mixed hardwoods	35
	KY-2	Mined	Mixed hardwoods	35
	KY-3	Mined	White pine/loblolly pine	40
	KY-4	Mined	Loblolly pine	33
Ohio	***OH-C***	*Natural*	*Oak/tulip poplar*	***59 †***
	OH-1	Mined	Mixed hardwoods	50
	OH-2	Mined	Mixed hardwoods	50
West Virginia	***WV-C1***	*Natural*	*Oak/tulip poplar*	***62 †***
	WV-1	Mined	White pine	38
	WV-C2	*Natural*	*Oak/tulip poplar*	***60 †***
	WV-2	Mined	White pine	28
Pennsylvania	***PA-C***	*Natural*	*Oak/tulip poplar/cherry*	***62 †***
	PA-1	Mined	White pine/Scots pine	40
Virginia	***VA-C***	*Natural*	*Oak/tulip poplar*	***72 †***
	VA-1	Mined	White pine	20

† Represent average age of trees measured on non-mined reference sites.

Site index of each tree species on all sites was standardized to the site index of a single species, white oak at base age 50 years (Doolittle, 1958). Similar to the site index conversion procedure used by Rodrigue (2001) we used site index tables and graphs that were most suitable for each site's location (Wenger, 1984).

We estimated above-ground and coarse-root biomass (kg dry weight) from species-specific tree diameter data for each tree tallied. These estimates were based on regression equations from the most recent literature (Jenkins et al., 2003). The above-ground and coarse-root weights were summed to produce an estimate of the total tree biomass in dry weight units. Total forest biomass included stem wood, stem bark, foliage, treetops, branches, stumps, and coarse roots. Total forest biomass was converted to kilograms of carbon with a conversion factor for different regional species groups (Birdsey, 1992). Carbon in ground layer woody or herbaceous biomass was not included because carbon estimates could not be generated for this portion of the forest community. However, carbon contained in these understory components is often ignored in biomass estimates because it only amounts to 1 to 2% of the aboveground carbon content (Birdsey, 1992; Bormann and Likens, 1979).

A soil pit was dug to a depth of 1.5 m at the four plot centers on each site (Fig. 2) to develop estimates of soil carbon. Pits were described using standard soil survey techniques to obtain total depth, horizon depth, and percent coarse fragments greater than 7.6 cm. Loose samples and duplicate bulk density samples were collected from each horizon. Soil samples were air-dried, sieved (2 mm), and weighed to determine coarse fragments (< 7.6 cm). All soil carbon determination procedures were performed on the sieved 2-mm fraction. Soil properties were analyzed on samples from all horizons found in the profiles. Bulk density, corrected for coarse fragment content, was determined using soil cores. Organic carbon was determined by the Walkley-Black wet oxidation procedure (Nelson and Sommers, 1982). This procedure is used to better discriminate between recently plant-derived pedogenic carbon and geologically-derived geogenic carbon in coal. Litter layer estimates were generated from four 0.25 m^2 random samples at each measurement plot and bulked to form a 1 m^2 sample. Bulked samples were dried, ground, and total carbon was determined with a LECO carbon analyzer. Litter layer estimates were corrected for ash and the mineral material that the samples contained. Total forest carbon, litter layer carbon, and soil organic carbon in kilograms per hectare were converted to metric tons per hectare (Mg ha^{-1}). Results from regression analyses termed significant in this paper have a confidence level of $\alpha = 0.1$.

<u>Assumptions for Projecting Natural Site Carbon Pools in Time</u>

In order to achieve our second objective of comparing carbon sequestration in forests on mined and non-mined land, we projected, by location, natural site carbon pools to the age of their corresponding mined sites. Age projection techniques were applied both to ‘grow’ (IL-C and IN-C) and to ‘reduce’ (KY-C, OH-C, WV-C1, WV-C2, PA-C, and VA-C) the present biomass of the natural forest stands to the biomass levels associated with earlier or later ages. Tree measurements, including stem cores for the last 10 years of stand development and bark thickness, were used to generate regression equations for predicting DBH by tree species at any age (Rodrigue, 2001).

Species with similar growth characteristics were grouped together in order to increase the amount of tree measurement data that was used in each per tree species group regression analysis (Rodrigue, 2001). The following lognormal linear regression model was used:

$$\ln(Core_{10}) = b_0 + b_1\left(\frac{1}{DBH_{10}}\right) \qquad \textbf{[1]}$$

where:

$\ln(Core_{10})$ = the natural log of the 10-year DBH increment

b_0 = intercept coefficient

b_1 = slope coefficient

DBH_{10} = tree diameter outside bark at 10 years prior to current age.

For example, using the regression equation for the pitch pine species group, $\ln(\mathrm{Core}_{10}) = -0.2856 + 0.9579\ (1/\mathrm{DBH}_{10})$, we estimated that the 1 year DBH increment increase for a 4 inch (DBH_{10}) and a 25 inch (DBH_{10}) tree was 0.096 inches and 0.078 inches, respectively.

Due to a paucity of information in the literature relative to changes in soil carbon pools with time under tree vegetation cover, we assumed that soil carbon in our natural sites was in equilibrium with the rest of the forest ecosystem components. Therefore, we assumed negligible changes in natural site soil carbon during a period of 50 years or less of forest stand development.

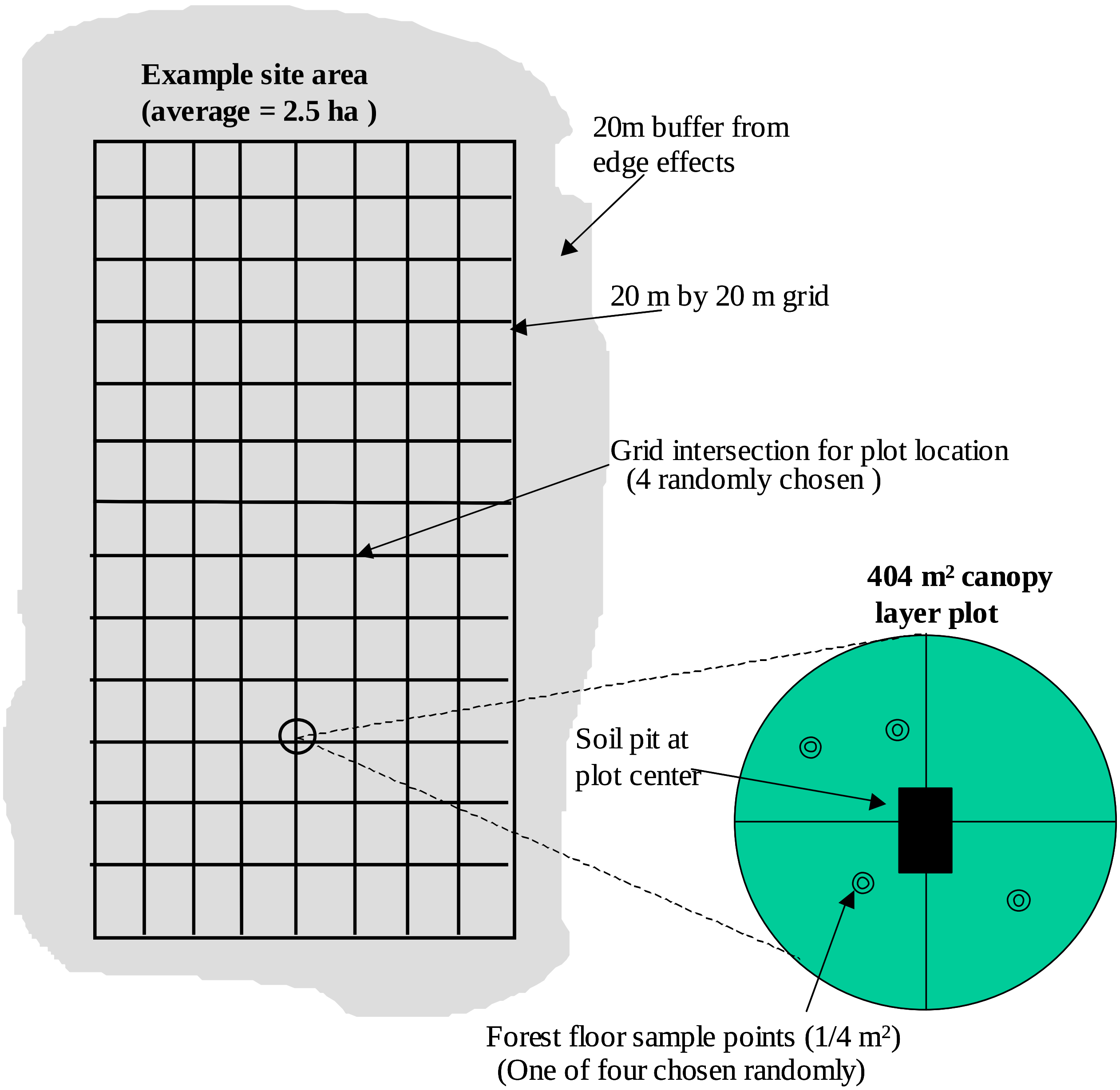

Figure 2: Typical site layout and data collection plot diagram for 8 non-mined (natural) and 14 mined sites in the Midwestern and Appalachian coalfields.

Forest floor biomass accumulation is a function of many environmental factors as well as tree species composition (Fisher and Binkley, 2000). However, considering that our natural stands grew under favorable climatic conditions characteristic of a typical temperate region of the United States, and the fact that these natural stands were 40 years or older and comprised primarily of mixed hardwood species, we assumed that the natural site litter layer biomass, hence the litter layer carbon pool, was in equilibrium as well (Fisher and Binkley, 2000).

Assumptions for Ecosystem Carbon Prediction using Multivariate Models.

We assumed that litter layer and soil carbon pools follow the same trend of carbon stock change as that of the tree carbon pool. The latter assumption was justified by the fact that the major source for terrestrial carbon input is the atmospheric CO_2 that is captured by the tree canopy. Hence, the greater the cumulative leaf area of a forest ecosystem the greater the inputs into the other ecosystem components resulting in an increase in total sequestered carbon per unit area of forested land.

Average ecosystem carbon estimates were computed for all sites by summing the simple averages for tree, litter layer, and soil carbon data from the four replicate plots that were measured at each location. Similarly, average site index and average stand age were calculated. We used standard regression procedures (proc REG) in SAS statistical software (SAS Institute Inc., Cary, NC) to generate multivariate regression models using site index (SI, feet for white oak at base age 50 years) and stand age (years) as the independent variables and total ecosystem carbon (Mg ha^{-1}) as the dependent variable.

We based our multivariate regression equations on well-established and widely-used tree growth and yield models (Brender, 1960; Nelson et al., 1961; Clutter, 1963; Brender and Clutter, 1970). The final regression model that was chosen had the following general format:

$$\ln(C_{ecosystem}) = b_0 + b_1(SI) + b_2(Age) + b_3(SI^2) + b_4\left(\frac{1}{Age}\right) + b_5\left(\frac{1}{Age^2}\right) + b_6\left(\frac{SI}{Age}\right) \qquad \textbf{[2]}$$

where

$\ln(C_{ecosystem})$ = natural log of the total ecosystem carbon (Mg ha^{-1})

b_i = regression coefficient, i=0,1,2,…,6

SI = average site index (feet for white oak at base age 50 years)

Age = average stand age

Ecosystem carbon for the natural sites was modeled using this general model. The regression model as well as each model component (i.e. *SI* versus SI^2 versus 1/Age) was statistically significant at the 0.1 confidence level. We then applied this same model to the mined site total carbon data. Finally, both regression models were plotted on a 3D diagram showing total carbon estimates for natural and mined sites across the spectrum of SI and stand age. The latter 3D representation of carbon estimates as a function of time and SI allowed for important inferences to be made about the effect of surface coal mining on forest productivity and the potential of mined sites to sequester carbon relative to that of non-mined natural stands.

Results and Discussion

In all cases, the carbon distribution among tree, litter, and soil components was more variable on mined sites (Table 2). The lower variation within the natural sites reflects the uniformity that develops in the tree community, litter layer, and soil during millennia of development, while mined site variation reflects a variety of site and stand conditions including age, tree species, mine soil construction, and site productivity. The tree carbon of natural sites varied between 57% and 66% of the total. On mined sites the range was 42% to 71% and was 54% to 72% for pine and hardwood stands, respectively. Litter layer carbon varied between 3% and 7% on natural sites, between 2% and 6% for hardwoods on mined sites, and between 4% and 16% for pines on mined sites. Soil carbon on natural sites varied between 27% and 40% of the total; on mined sites the range was 24% to 40% for hardwood sites and 14% to 46% for pine sites.

Tree Carbon

Carbon sequestered in tree biomass is a function of stand age, soil quality, and site and forest quality. The ratio of carbon on mined versus natural sites $\left\{\left(C_{Mined\_Sites}/C_{Natural\_Sites}\right)*100\right\}$ was used as a statistic for comparing mined site carbon sequestration potential of each forest ecosystem component with that of the natural sites. We assumed that natural site carbon estimates depicted a logical reference for carbon capture on undisturbed forested sites. Percent ratio greater than 100% means that mined sites sequestered carbon quantities that were greater than those on natural, non-minied, adjacent sites.

The ratio for the tree component of pine stands ranged between 39% (VA-1) and 145% (KY-4) with an average ratio of 89% (Fig. 3). The ratio for hardwoods ranged from 67% (IN-1) to 135% (OH-1) with an average of 95%. On average, hardwoods had a slightly greater carbon sequestration potential than pines.

Carbon recovery was greater than 100% for some hardwood (KY-2, OH-1, and OH-2) and pine (WV-2, KY-4, and KY-3) stands (Fig. 3). Carbon recovery levels on these mined sites indicated that reclamation procedures created growth conditions similar to or better than those on the adjacent non-mined sites. Properly reclaimed mined sites appear to ameliorate growth limiting conditions such as soil fragipans (OH-1 and OH-2) and shallow depths to bedrock (KY-2, KY-3, KY-4, and WV-2). Mining operations and the proper reclamation of the sites in Ohio, West Virginia, and Kentucky created more productive sites by eliminating root-limiting conditions.

Carbon present within the developing tree biomass (stem wood, stem bark, foliage, treetops, branches, stumps, and coarse roots) on natural sites ranged from 97 to 156 Mg ha^{-1} (Table 2). Mined-site tree carbon ranged from 76 to 128 Mg ha^{-1} (hardwood) and ranged from 43 to 139 Mg ha^{-1} (pine). Carbon found in tree biomass was comparable to other natural forests in the East, though tree carbon pools vary from study to study depending on site productivity, site age, tree species, management impacts, and local topography and climate. Little has been done to quantify the carbon pools associated with tree biomass of mature, planted forests on mined sites. (Ashby et al., 1980; Burger et al., 2003).

Tree carbon averaged 126 Mg ha^{-1} for our natural sites and 106 Mg ha^{-1} and 92 Mg ha^{-1} for mined site hardwood and pine stands, respectively. Carbon associated with tree biomass of hardwood forests in Indiana were measured by Kaczmarek et al. (1995). Our estimates for both natural and mined hardwood sites in Indiana and western Kentucky are well within the range of their carbon estimates, which were between 61 and 117 Mg ha^{-1}.

Richter et al. (1995) found 140.6 Mg ha^{-1} carbon in the tree biomass of a 35-year-old loblolly pine site in South Carolina. Within our study, sites KY-3 and KY-4 both contained loblolly pine. They had 106 and 131 Mg ha^{-1} of carbon in total woody plant biomass at ages 40 and 33, respectively. Pine sites in the Appalachian region (WV-1, WV-2, PA-1, VA-1) were dominated by white pine, averaging 87.5 Mg ha^{-1}. These pine sites compared favorably with carbon estimates for mixed pine and hardwood canopies on southern and western aspects in North Carolina (Vose and Swank, 1993).

Table 2: Carbon sequestered by ecosystem component of even-aged stands on 8 non-mined (natural) and 14 mined sites in the Midwestern and Appalachian coalfields. State abbreviations denote the location of each site.

Site	**Tree Carbon**	**Litter Layer Carbon**	**Soil Carbon**	**Total Carbon Sequestered**
	------------	Mg ha^{-1}	------------	
Natural Sites:				
IN-C (40) ††	113 (59) †	5 (3) †	74 (39) †	192
IL-C (43)	156 (58)	7 (3)	108 (40)	271
KY-C (52)	102 (57)	11 (6)	66 (37)	179
OH-C (59)	97 (61)	9 (6)	53 (33)	159
WV-C2 (60)	137 (61)	8 (4)	81 (36)	226
PA-C (62)	120 (66)	13 (7)	49 (27)	182
WV-C1 (62)	132 (61)	10 (5)	73 (34)	215
VA-C (72)	148 (65)	15 (7)	66 (29)	229
Average:	**126 (61)**	**10 (5)**	**71 (34)**	**207**
Mined Sites:				
Pine				
VA-1 (20)	43 (42)	16 (16)	44 (43)	103
WV-2 (31)	139 (67)	20 (10)	48 (23)	207
KY-4 (33)	131 (68)	23 (12)	39 (20)	193
WV-1 (38)	81 (70)	18 (16)	16 (14)	115
KY-3 (40)	106 (63)	7 (4)	55 (33)	168
PA-1 (40)	87 (71)	19 (15)	17 (14)	123
IN-2 (50)	56 (44)	13 (10)	58 (46)	127
Average:	**92 (61)**	**17 (12)**	**40 (28)**	**148**
Hardwood				
KY-1 (35)	76 (54)	8 (6)	57 (40)	141
KY-2 (35)	93 (66)	4 (3)	44 (31)	141
IL-2 (43)	122 (71)	8 (5)	42 (24)	172
OH-1 (50)	125 (64)	4 (2)	67 (34)	196
OH-2 (50)	114 (72)	5 (3)	39 (25)	158
IL-1 (54)	128 (70)	7 (4)	48 (26)	183
IN-1 (55)	80 (60)	21 (16)	32 (24)	133
Average:	**106 (65)**	**8 (5)**	**47 (29)**	**161**

† Numbers in parentheses (carbon values) indicate carbon distribution as a percent of the site total.

†† Numbers in parentheses (site) indicate average stand age.

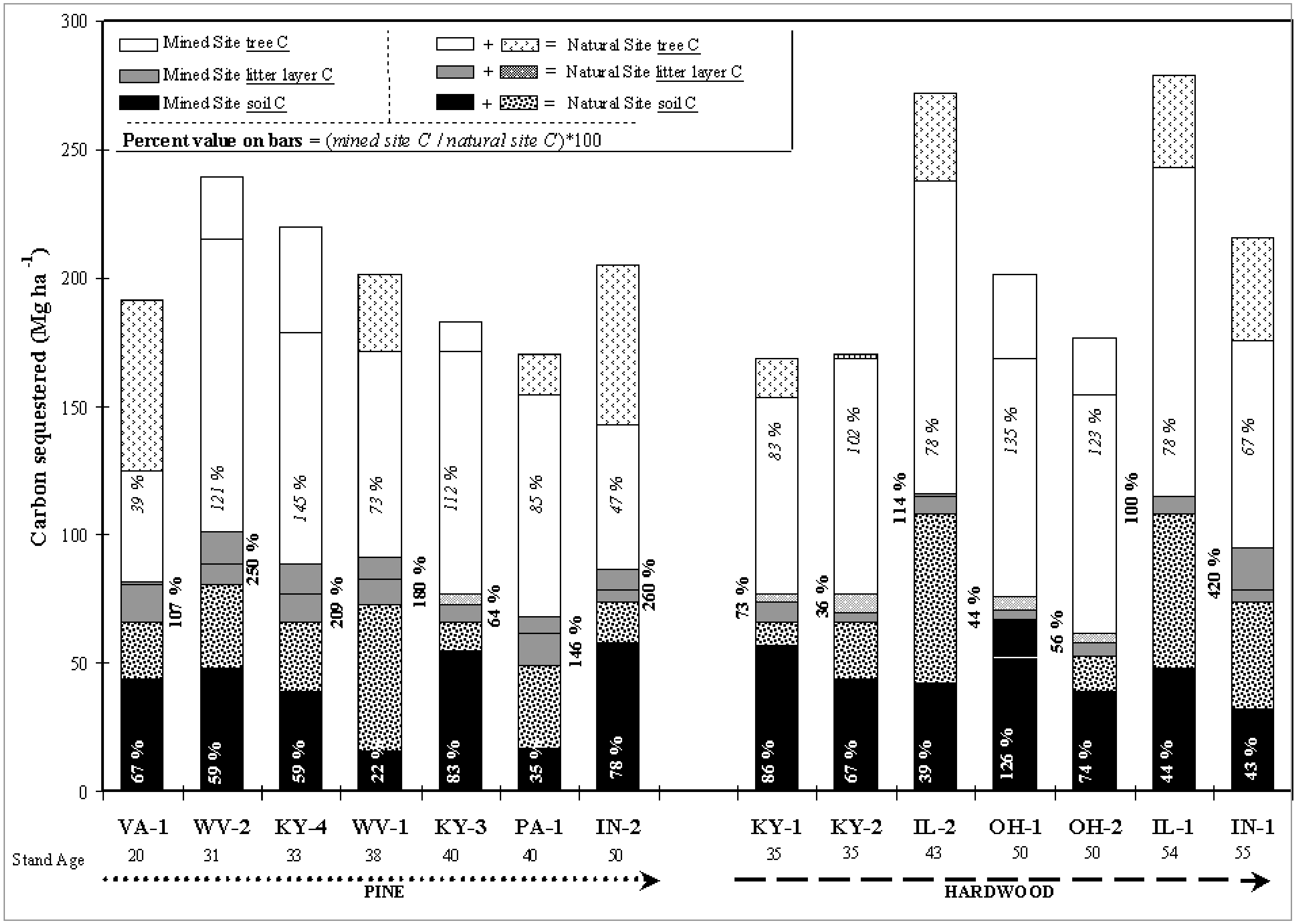

Figure 3. Total carbon captured in forest ecosystem components (tree, litter layer, soil) of 14 forested mined sites (pine and hardwood forests) and corresponding natural, non-mined reference sites (carbon values for the non-mined sites were projected to the age of the mined sites) located in the Midwestern and Appalachian coalfields of the US. Study site locations are arranged on the horizontal axis in age-increasing order. State abbreviations denote the location of each site

Overall, these mined sites were new forest communities that, in some cases, accumulated nearly as much carbon in the tree biomass as that sequestered in trees on the natural sites. Most of these new forests contained valuable species, trees were well spaced, and especially on low quality sites, these new forest systems had the potential to develop greater amounts of tree carbon per unit area than understocked, high-graded forests commonly found in the eastern U.S.

Litter Layer Carbon

Natural-site litter layer carbon pools ranged from 5 to 15 Mg ha^{-1} (Table 2). Litter layer carbon pools on mined sites ranged from 4 to 8 Mg ha^{-1} (excluding IN-1 site) and ranged from 7 to 23 Mg ha^{-1} for hardwood and pine stands, respectively. The IN-1 (21 Mg ha^{-1}) Indiana site had a unique tree species composition including a significant pitch pine component that may be the reason for its relatively high litter layer carbon accumulation.

Litter layer carbon estimates compared favorably with other investigations. Overall, our litter layer carbon estimates from natural sites averaged 10 Mg ha^{-1} and those from mined sites averaged 8 Mg ha^{-1} (hardwood) and 17 Mg ha^{-1} (pine). Litter decomposition rates differ with litter type, a result of variation of litter quality, litter chemical composition, availability of nutrients, particularly nitrogen, from other site resources, and climatic factors (Vogt et al., 1986).

The mined to non-mined litter layer carbon ratio ranged from 64% (KY-3) to 260% (IN-2) and ranged from 36% (KY-2) to 114% (IL-2) (excluding IN-1 site with 420% ratio) for pine and hardwood stand, respectively (Fig. 3). The average for pine stands (173%) was almost 1.5 times greater than the average for hardwood sites (120%). A ratio greater than 100%, particularly in pine stands, may indicate failure to recycle C and other nutrients causing significant litter layer build-up.

Litter layer carbon pools from other studies in the eastern U.S. ranged from 4 to 14.4 Mg ha^{-1} depending on age and forest species composition (Hoover et al., 2000; Kaczmarek, 1995; Van Lear et al., 1995; Vose and Swank, 1993). However, sites with higher conifer components tend to develop greater carbon pools within the litter layer. In Ohio, Vimmerstedt et al. (1989) found that hardwood litter layer carbon pools (3 Mg ha^{-1}) were significantly lower than litter layer carbon pools under pine sites (8 Mg ha^{-1}). On a 35-year-old loblolly pine site in the piedmont of South Carolina, litter layer carbon averaged 32.8 Mg ha^{-1} (Richter et al., 1995). Our 33-year-old loblolly pine mined site in western Kentucky (KY-4) averaged 23 Mg ha^{-1}.

Mined site litter layers also appeared to be approaching a steady state relative to carbon accumulation. Van Lear et al. (1995) found that pine litter layers in the southeast tend to reach a steady state 15 to 20 years after a disturbance such as logging. Yanai et al. (2000) found that litter layers in logged northern hardwood forests increased with age after disturbance until about 50 to 55 years. However, over the chronosequence of their study, litter accumulation was also related to the logging practice used on each site.

Soil Carbon

Unlike tree and litter layer carbon, soil carbon contents on mined sites were consistently lower than the natural soil carbon pool. The average mined to non-mined ratio was 57% (range from 22% to 83%) and was 68% (range from 39% to 126%) for pine and hardwood stands, respectively (Fig. 3). Of the three ecosystem components the soil has the greatest potential for sequestering and storing additional carbon.

Natural site soil carbon ranged from 49 to 108 Mg ha^{-1} (Table 2). The amount of carbon in the mine soils ranged from 24 to 40 Mg ha^{-1} under hardwoods, and ranged from 14 to 46 Mg ha^{-1} under pines. Average natural site soil carbon levels were similar to estimates for temperate forest soil carbon levels reported in the literature. Post et al. (1982) reported average soil carbon levels of 79 and 60 Mg ha^{-1} within 1 m for dry and moist warm temperate forests, respectively. Researchers in the eastern U.S. reported carbon levels for depths from 0.5 m to bedrock ranging between 36 and 130 Mg ha^{-1} (Hoover et al., 2000; Johnson et al., 1995; Kaczmarek, 1995). Our natural sites averaged 71 Mg ha^{-1} and mined sites averaged 40 Mg ha^{-1} and 47 Mg ha^{-1} for hardwood and pine stands, respectively (Table 2).

The mined site average soil carbon was comparable to that of a degraded natural pine site on the Piedmont of South Carolina (Van Lear et al., 1995) that had 37.2 Mg ha^{-1} carbon within 1 m. Prior to pine establishment, poor farming practices severely eroded this site, resulting in loss of the surface horizons. Mined soil carbon pools also correlated well with carbon pools reported in other investigations. Akala and Lal (1999) reported that 30-year-old reforested mined sites (to 0.5 m) contained 51.5 Mg $ha^{-1}$of soil carbon; 50-year-old sites contained 54.9 Mg ha^{-1}. Sites approximately 30 years old in our study contained 47 Mg ha^{-1}, while 50-year-old mined sites contained an average of 55 Mg ha^{-1}.

Total Ecosystem Carbon

Total carbon sequestered on natural reference sites ranged from 159 to 271 Mg ha^{-1}, with an average of 207 Mg ha^{-1} (Table 2). Total carbon sequestered on mined sites ranged from 103 to 207 Mg ha^{-1} in pine stands and ranged from 141 to 196 Mg ha^{-1} in hardwood forests. The average across sites planted to pine (148 Mg ha^{-1}) was lower than that of sites planted to hardwoods (161 Mg ha^{-1}).

Most of the carbon present on both reference and mined sites was associated with the total tree biomass (Table 2). Generally, the relative carbon allocation in trees was greater than that in soil with the exception of two mined-site pine stands (VA-1 and IN-2). These two exceptions are examples of the significant effect of stand age as a factor in pine stand development and tree growth. The white pine stand (VA-1) was 20 years old at time of measurement and the pitch pine stand (IN-2) was 50 years old. At an early age, trees are in the initial phase of accumulating biomass, hence carbon sequestration is accelerating. However, in the second case, tree biomass is likely being relocating to the soil carbon pool as the old pine stand deteriorates. The tree carbon contained an average of 61% of the total sequestered carbon on natural sites. Equally, on mined-site pine stands, the tree carbon represented 61% of the total ecosystem carbon. For hardwood stands the ratio was 65%. Natural forest litter layers contained 5% of the total carbon, and mined site litter layers contained 5% (hardwood) and 12% (pine). The soils of natural and mined sites contained 34% and 29% (hardwood) and 28% (pine) of the sequestered carbon, respectively.

Total Carbon Inventory Models

Multivariate regression models for total carbon as a function of stand age and SI were created for both natural and mined sites. Carbon content response surfaces built upon statistically significant regression equations are shown in three-dimensional perspective for a better visualization Fig. 4).

The regression model for the natural sites (P=0.0021) explained about 68% (Adj-R^2=0.68) of the total variation among the observed average total carbon amounts captured on natural sites (Fig. 4). This model form is well-established and widely used to represent biomass production as a function of age and site quality. All regression components for our natural site data were statistically significant ($P<0.1$). This model was also applied to the mined-site data. The model was also significant (P=0.0642) and explained 28.3% (Adj-R^2=0.28) of the total variation among observed total carbon on mined sites (Fig. 4). Both models appeared to be good representations of stand dynamics and biomass accumulation in forest ecosystems across the spectrum of SI and stand age. An example of the good integrity of both models is the representation of biomass accumulation rates for low SI (poor) and high SI (good) natural and mined sites. At early stages of stand development (< 30 years) on fertile sites (SI > 100 ft) both natural and mined sites accumulate biomass, hence accumulate carbon, at much faster rates (steeper slopes) than that on poor sites. In fact, on poor sites (for ages beyond 15 years), the rate of carbon accumulation is minimal.

Site index and stand age affected differently the carbon sequestration rates on both mined and natural sites. Carbon accumulation on both mined and natural sites increased exponentially with increases in site index (SI), and increased asymptotically with stand age increases (Fig. 4). However the rates of increase differed between the natural and mined sites. As shown on Fig. 4, an increase in SI on natural sites resulted in a steeper response surface relative to the response surface for the mined sites.

Combining both the mined and natural site response surfaces from Fig. 4 shows the influence of mined land site quality on carbon sequestration compared to the undisturbed reference condition. Clearly depicted in Fig. 5 is the convergence of both regression planes at approximately SI 45 (Fig. 5). This corroborates the observations and reports of several researchers that forest productivity of pre-SMCRA mined sites is as good or better than the productivity of poor-quality sites prior to mining (Ashby et al., 1980; Burger et al., 2003). Improved forest productivity as a result of mining is usually attributed to the break up of natural soil fragipans, bedrock and other root-impeding layers. On the other hand, the models show that forests growing on mined sites that had a SI > 50 prior to mining are not as productive after mining. The higher the original forest site quality, the less likely productivity is restored, and the greater the disparity between pre- and post-mining carbon sequestration potential.

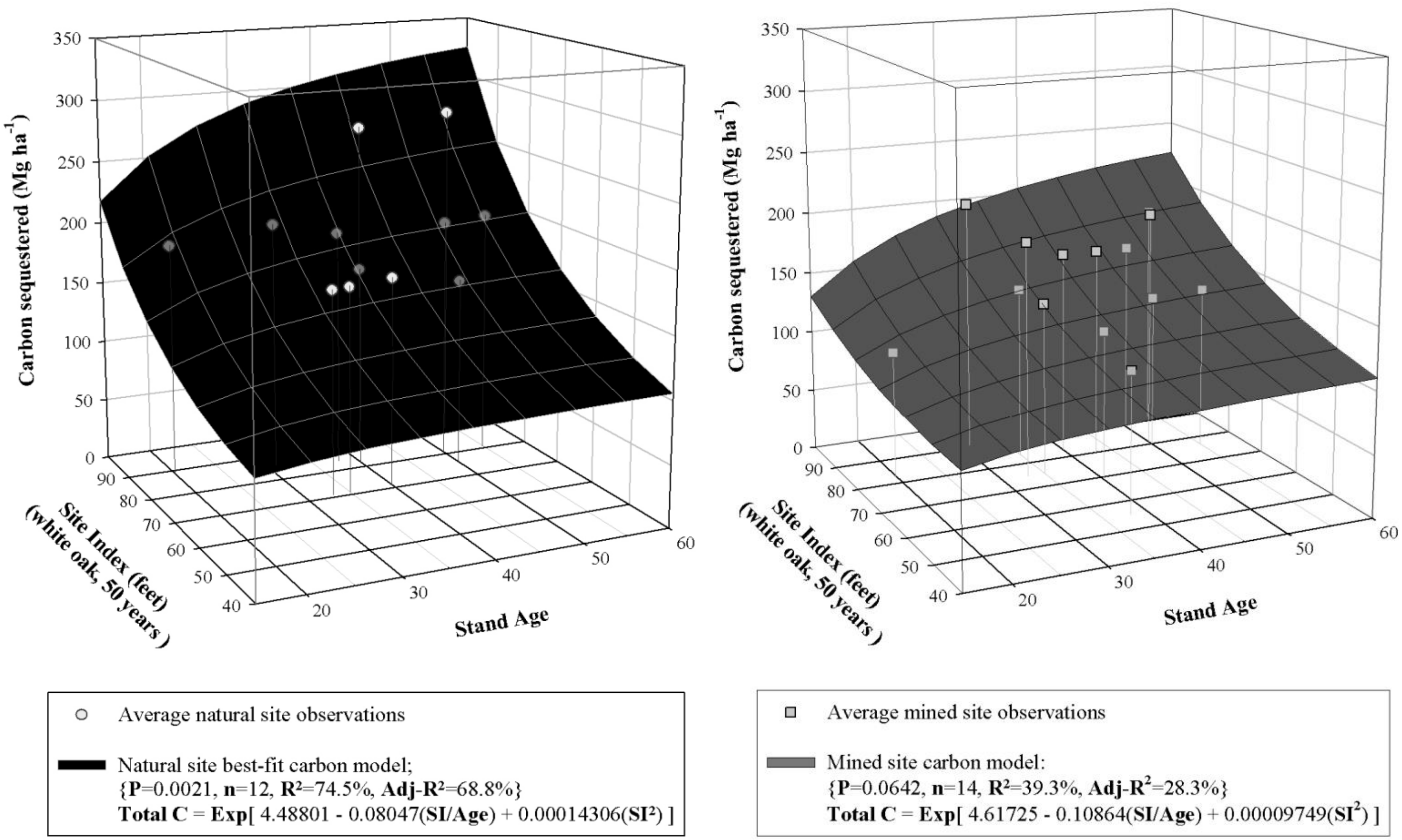

Figure 4. Average total ecosystem carbon sequestered on 8 non-mined reference sites (left) and 14 mined sites (right) located in the Midwestern and Appalachian coalfields of the US. Multivariate regression models were used to create the corresponding carbon response surfaces using site index and stand age as independent variables. The eight non-mined sites were projected to the specific age of each of their corresponding adjacent mined sites, thus yielding twelve projected non-mined reference carbon values.

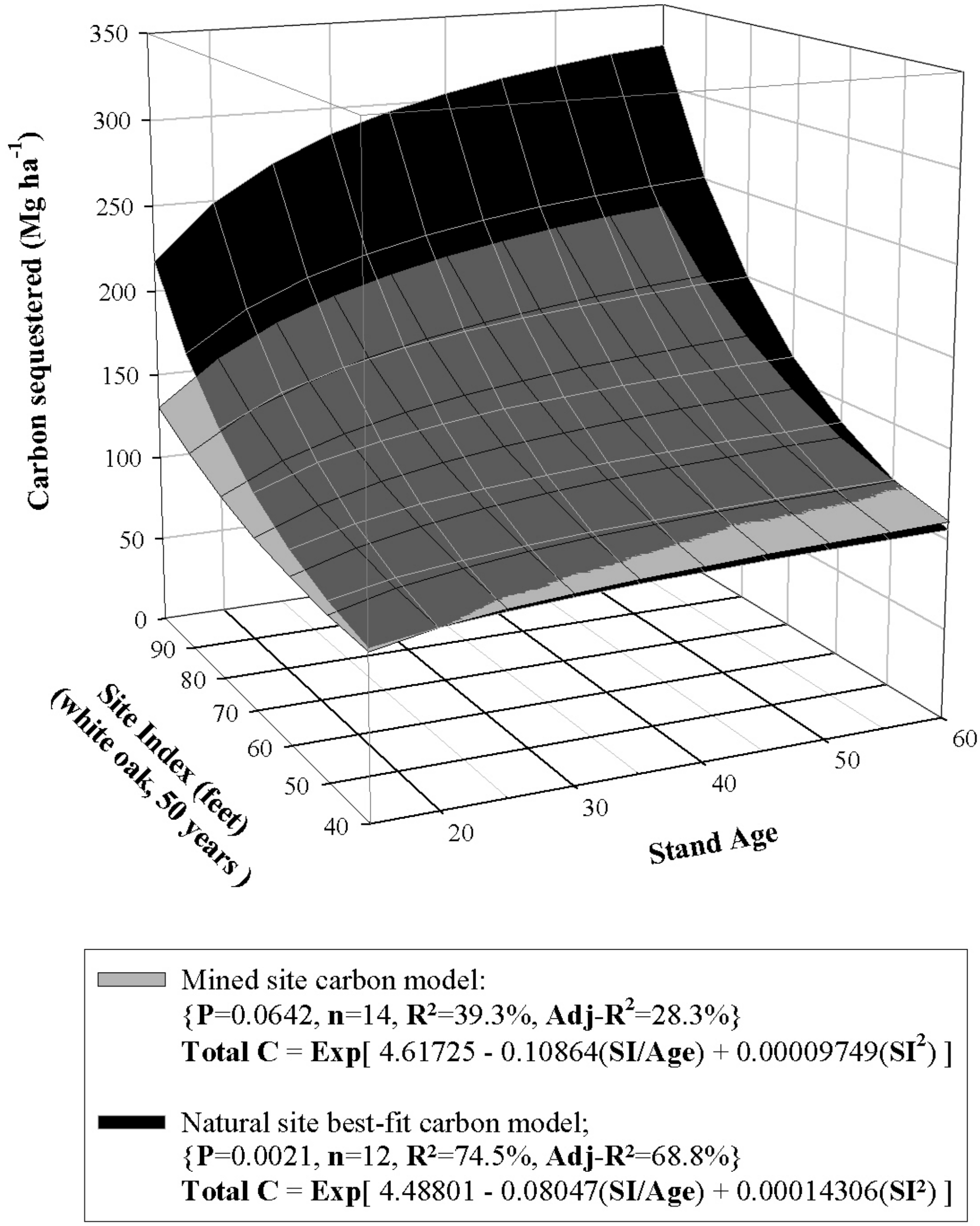

Figure 5. Multivariate regression models for total forest ecosystem carbon storage based on average site data for forested non-mined (darker surface) and forested mined sites (lighter surface) located in the Midwestern and Appalachian coalfields of the US. The mined site response surface is below that of the non-mined sites across the entire range of site index and age except for the region confined between site index 40 and 50 for stand age greater than 20 years

Because of the limited fit (Adj-R^2=28.3%) of the natural site model to the mined site data, we explored the possibility that a different regression model would better represent total ecosystem carbon accumulation on mined sites. Mined sites are very different from natural sites due to the elimination of natural soil, changed hydrology, and different distributions of flora and fauna; therefore, it is not unreasonable to believe that carbon would accumulate differently as a function of forest age and mine site quality. We used the base model in Eq.2 and re-analyzed the mined site data using the same steps as previously described. The new model, as well as each of the model components, was statistically significant ($P<0.1$). The goodness of fit of the new model nearly doubled, increasing the r-squared value from 28.3% to 48.6% (Fig. 6).

Biologically the new model is very reasonable. The response surface depicted similar patterns of carbon accumulation across the spectrum of SI and age. However, the increase in stand age affected carbon sequestration rates differently than previously discussed. Carbon sequestration peaked at an approximate age of 35 years across any level of site index, after which it decreased as the stands aged (Fig. 6). We attribute this response to the significant component of older pine stands in the mined site data set. Pine stands tend to deteriorate at ages greater than 40 years, characterized by tree mortality and carbon efflux to the atmosphere and the soil carbon pools. This response was particularly evident in our 50-year-old Indiana pitch pine mined site (IN-2).

Given our limited data set, species- and management-specific inferences can not be made. However, our goal is to include additional forested mined sites and their corresponding non-mined natural sites that would allow for species-specific estimates of carbon sequestration potential. We will also measure carbon sequestration potential of post-SMCRA mined sites and determine the influence and value of different forest management practices, including hybrid tree species, tillage, weed control and fertilization on long-term restoration of site productivity and carbon sequestration.

We will also refine our measurement and monitoring techniques to maximize the precision of our carbon estimates. Evidence from the literature suggests that the best current organic carbon determination techniques, including both wet and dry combustion methods, invariably include some amount of geogenic carbon in the estimate (Thurman and Sencindiver, 1986; Indorante et al., 1981; Pederson et al., 1978; Cummins et al., 1965). If this is the case, then mine soil pedogenic carbon estimates are actually lower than projected, and replenishment of soil carbon levels may take longer than indicated.

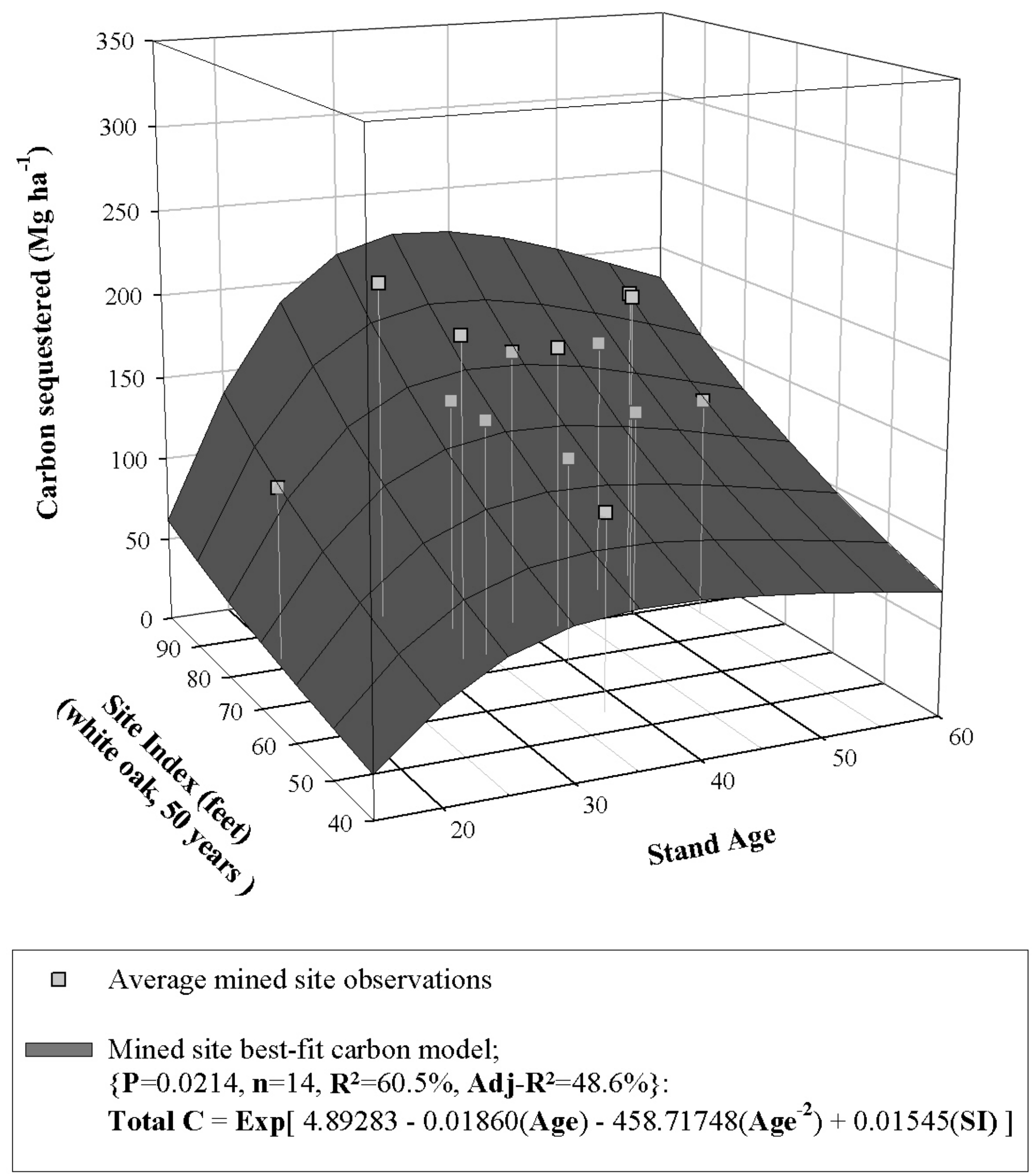

Figure 6. Average total ecosystem carbon sequestered on 14 mined sites located in the Midwestern and Appalachian coalfields of the US. The figure depicts a carbon storage response surface generated by using a multivariate regression model with site index and stand age as independent variables.

Conclusions

The development of productive forests on reclaimed land satisfies multiple goals. Successful reforestation on productive minelands meets SMCRA guidelines that require the return or enhancement of pre-mining productivity levels. Reforestation also establishes a long-term sink for atmospheric carbon. Land that has been mined for coal increases atmospheric carbon via land use change and by producing a carbon-based fuel. Considering that very little organic carbon is present on a recently reclaimed mined site, there is great potential for sequestering carbon by restoring the forest to a level of productivity equal to or greater than that present before mining.

Mined soil organic carbon levels were lower than average natural sites due to the pre-law mining process which disrupts the biogeochemical cycle of all elements, including C. By removing the forest and soil fauna and flora, the carbon cycle is breached and sequestration is interrupted. Reincorporating organic matter into the soil requires establishment of a biological community, including plants for primary production, and soil fauna and flora to process the detritus.

Our results indicate that pre-SMCRA surface coal mining procedures used in the Midwestern and the Appalachian coalfields of the USA degraded forest site quality and the potential to sequester carbon at pre-mining levels. Based on the carbon sequestration models generated in this study, the natural forest stands that were growing well on medium- to highly-productive forest sites (SI greater than 50 ft) produced more tree biomass and sequestered more carbon than mined sites across the same spectrum of stand age (15 to 60 years). Research investigating the effects of different forest management techniques on carbon sequestration potential of mined lands planted to forests is currently underway on three mined sites in Ohio, West Virginia, and Virginia.

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