CARBON ACCUMULATION POTENTIALS OF POST-SMCRA COAL-MINED LANDS[1]

C.E. Zipper, J.A. Burger, J.M. McGrath, and B. Amichev[2]

Abstract: Many coal-surface mines reclaimed under SMCRA in eastern US were not restored to forest vegetation and are not currently in a managed use. Reforestation of these lands could provide benefits including timber production, watershed protection, and carbon (C) sequestration. Our objectives were to determine the suitability of eastern US coal-mined lands' soil properties for reforestation and to estimate the cumulative potential of these lands to accumulate C through reforestation. Databases of coal mining permits issued under SMCRA were obtained for KY, OH, VA, and WV, and 20 bond-released permits were selected in each state using an area-weighted randomization procedure. Access permissions were obtained for 25 sites (6 each in OH, KY, and VA, and 7 in WV), each of which was sampled at up to 10 randomly selected points. At each sampling point, soil physical properties were determined for the top 30 cm, and soil chemical properties were determined for surface (0 – 10 cm) and subsurface (10 – 30 cm) soil layers. Measured soil properties were used to estimate forest site productivity (SI50) using two methods, and each site's potential to accumulate C was estimated as a function of SI50 based on relationships derived from soil property and C accumulations on pre-SMCRA surface mines. Assuming these sites to be representative of eastern US mined lands, and that 50% of eastern US post-SMCRA mined lands could be available for reforestation under sufficient financial incentives, post-SMCRA mined lands reforested with pine species have the potential to accumulate on the order of 1.6 Tg C yr^{-1} over a 30 year rotation, equivalent to about 0.2% of projected US coal-combustion C emissions.

Additional Key Words: Carbon sequestration, mine reforestation.

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Introduction

Large quantities of carbon dioxide (CO_2) and other infrared-absorbing "greenhouse" gases (GHGs) are being emitted to the atmosphere globally by fossil-fuel combustion for energy utilization and other activities. Scientific observations indicate atmospheric GHG concentrations are rising steadily, creating potential influence on climate and consequent negative impacts on the global environment and economy (McCarthy *et al.* 2001).

Given the dependence of current living standards in industrialized nations on energy usage, growing populations and increasing energy utilization in emerging economies, and the limitations to fossil-fuel alternatives as energy sources available for near-term and widespread implementation, many have called for measures to reduce energy-related CO_2 and other GHG emissions to the atmosphere while offsetting (or sequestering) some portion of those GHG emissions that continue to occur. While the long-term solution to global climate problem is likely to include technologies such as C capture from fossil-fuel combustion and geologic storage (IEA, 2004; IPCC 2005), these technologies remain under development. In contrast, sequestration methods that rely on management of agricultural and forested systems (terrestrial sequestration) can be implemented with current technologies.

This study assesses the potential for conversion of lands mined under the Surface Mining Control and Reclamation Act (SMCRA) to forest for the purpose of sequestering atmospheric C. Research objectives were to determine the suitability of eastern US coal-mined lands' soil properties for reforestation and to estimate the potential of these lands to accumulate C if reforested.

Experimental Methods

Identify and Sample Mine Sites

Twenty bond-released SMCRA mine permits each in Kentucky, Ohio, Virginia, and West Virginia were selected from permitting databases maintained by state agencies using a randomized procedure with each permit weighted by acreage. An effort was made to identify and contact landowners so as to obtain site access permissions. For sites where access permission could not be obtained but knowledgeable parties communicated opportunities to access nearby sites with similar characteristics, these sites were sampled as substitutes for the original sites. Sampling locations were located on each site using a randomization procedure.

Field parameters measured at each sampling location include depth of penetration by a hand-operated screw auger ("auger depth") (Jones *et al.* 2005). Herbaceous biomass was sampled 1 x 1/4 m quadrats (3 per sampling site) and oven dry weights were obtained. Vegetation characteristics within a 20m radius of the sampling site were estimated as proportionate coverages representing bare ground, open water, herbaceous species, shrub species, and forest species; dominant species, species mixes, and/or species groups within each vegetative component were also recorded; where dominant communities varied within the 20-m radius, the area was sketched and the dominant species, mixes, and/or groups within the each sub-area were recorded. Estimated percent compositions recorded for each sampling location were averaged by mine site.

Soils were sampled by excavation of an approximate 30 x 30 x 30 cm cylindrical volume, separated at 10cm depth into surface and subsurface fractions. The volume of the excavated cavity was determined by filling the hole with small spheres and determining volume occupied by the spheres upon retrieval. Soil samples were bagged and weighed, and a subsample of the soil-sized fraction was removed to determine moisture content. After air drying, soil samples were sieved at 2 mm and the coarse fragment content (>2mm) was determined as a mass proportion of the total sample. Bulk density of the soil-sized fraction was determined as the dry-mass-to-volume ratio, assuming a coarse-fragment density of 2.4 g/cm^3. Particle size distribution of the soil-sized fraction (% sand, % silt, % clay of the soil-sized fraction) was determined using the hydrometer method (Gee and Bauder, 1986). Bulk density of the soil-sized fragments was determined on a whole-soil basis (0 – 30 cm), while coarse fragment content and composition were determined separately for 0 -10 and 10 – 30cm depths. Particle size analysis was conducted on a composite sample (1/3 surface + 2/3 subsurface) of soil-sized fragments.

All soil chemical properties were determined separately for the surface and subsurface soil fractions. Soil pH was determined on a mixed suspension of 1:1 volume-to-volume ratio of soil material to distilled water (McLean, 1986). Soluble salts were determined using the method of Rhoades (1986) by measuring the electrical conductivity of a 1:2 volume:volume ratio of soil material to distilled water, and converted to a 1:5 soil:water ratio basis using a regression equation developed by measuring of 1:5 soil:water EC of 32 of the collected samples selected using a randomized procedure biased towards higher values so as to represent the full range of EC measurements (Fig. 1).

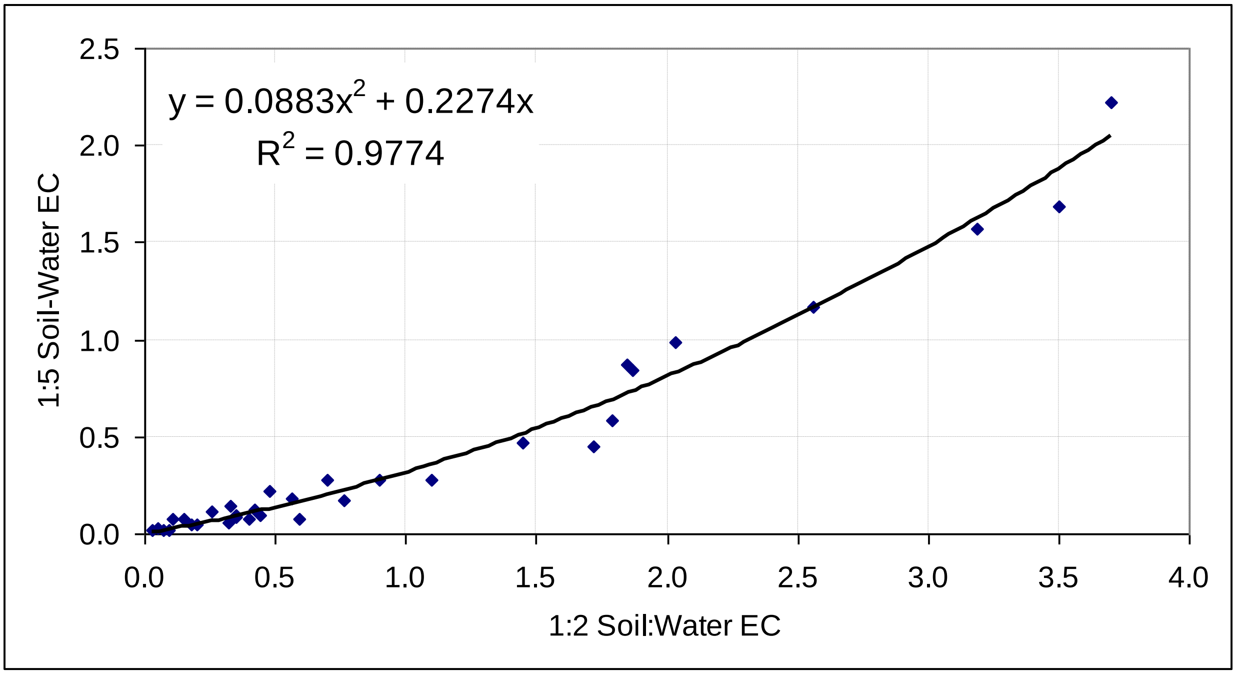

Figure 1. Correspondence of 1:5 soil:water EC and 1:2 soil:water EC for 32 soil samples selected to represent a range of measured 1:2 EC values, and the equation that was used to estimate equivalent 1:5 soil:water EC values based on measured 1:2 soil:water EC.

Sodium bicarbonate extractable P was determined using the method of Olsen and Summers (1986), and exchangeable cations (Ca, Mg, K, Na) were extracted with 1 M ammonium acetate (Thomas, 1986). Phosphorus and cations were determined using a Thermo Elemental ICAP 61E (Inductively Coupled Argon Plasma Atomic Emission Simultaneous Spectrometer) by Virginia Tech Soil Testing Laboratory. Exchangeable acidity was determined using the potassium chloride extraction technique (Thomas, 1986). Effective cation exchange capacity (ECEC) was estimated by summing the charge associated with exchangeable acidity and exchangeable Ca, Mg, K, and Na. Base saturation was calculated as the proportion of the ECEC occupied by base cations (Thomas, 1986). Total C and N were determined using a Leco C / N analyzer (LECO Corp, St. Joseph, MI).

Reclamation dates for sampling sites in KY, northern WV, and OH were estimated by applying best professional judgment while considering known information such as mine permit application and/or approval dates; performance-bond release dates (when available), recollections of contacts familiar with the sites; ages of planted eastern white pines (if present). For sites in southern WV and VA, normalized difference vegetation indices (NDVI, a spectral indicator of vegetation density) derived from Landsat satellite imagery dated 1987, 1988, 1994, 1998, and 2000 for the Virginia and southern West Virginia sites. A median reclamation age (calculated as 2005 minus estimated year of reclamation) was calculated for each site.

The forest productivity of each sampling site was estimated as 50-year site index for white oak (expressed in meters) using two methods.

Estimate Forest Productivities: Jones Model

Forest productivity "sufficiency curves" developed by Jones *et al.* (2005) were used to determine sufficiency levels for each soil measurement at each sampling location and a forest site productivity index was determined for each sampling location, also using Jones *et al.* (2005). Sufficiency values were assigned to soil parameters at each sampling location on a 0 – 1 scale, with 0.0 indicating poor forest site quality and 1.0 indicating superior quality. These values were combined to calculate a productivity index using the following equation:

$$PI_{JONES} = 0.44*S_{BD} + 0.28 * S_{AD} + 0.20\ S_{s+c} + 0.08\ S_{PH} \qquad (1)$$

Where:

PI_{JONES} = Productivity Index (Jones method).
S_{BD} = Bulk density of the soil-sized fraction (g/cm^3) sufficiency.
S_{AD} = Augur depth (cm) sufficiency.
S_{s+c} = Soil texture (% of soil-sized fraction comprised of silt + clay) sufficiency.
S_{PH} = Soil pH sufficiency.

Jones et al (2005) developed and validated this method using samples taken from the top 20 cm. Our sampling depths were 30 cm. For properties analyzed for the full 30 cm depth (texture, bulk density), measured values were used to determine sufficiency levels. For properties analyzed separately for 0-10 cm and10-30 cm layers (pH), a "whole soil" value was calculated by considering component values as proportionate to sampling depth.

A mean PI value was calculated for each mine site, and state and overall means were calculated from the mine-site means. The productivity index for each sampling site was converted to a 50-year site index for white pine, expressed in feet ($SI50_{WP}$), using an equation derived by Jones *et al.* (2005), Fig. 7:

$$SI50_{WP} = 117.74*PI_{JONES} + 15.588 \quad (2)$$

An equivalent 50-year white oak site index expressed in feet ($SI50_{WO}$) was calculated for each sampling location, using a relationship derived from Figure 1 in Doolittle (1958):

$$SI50_{WO} = 0.8627*SI50_{WP} - 5.7647 \quad (3)$$

Estimate Forest Productivities

Because the Jones method for estimating forest productivity relies primarily on physical parameters, utilizes a measure that proved difficult to apply with consistent results in the field (auger depth), and was validated using measurements from only a single species (eastern White Pine), the investigators developed an alternative method for estimating soil productivity, termed hereafter as the General Model.

Based on research experience (including Andrews et al, 1992; Jones *et al.* 2005; Showalter *et al.* 2006; Torbert *et al.* 1988; Torbert *et al.* 1992; and other studies), an expression for calculating a productivity index (PI_{GEN}) was developed (see Table 1):

$$PI_{GEN}= (S_{BD} + S_{CF} + S_{TX} + S_{BS} + S_{pH} + S_{EC} + S_{P}) / 7 \quad (4)$$

Equations used to generate sufficiency values are listed in Table 1. The adequacy of the PI_{GEN} as an indicator of site index was validated using data collected by Rodrigue (2001; see also Rodrigue and Burger 2004) in his study of forest site productivity in mined land forest sites in eastern USA. Using Rodrigue's data (mined sites only, excluding non-mined control sites; 3 to 4 sampling locations per site, at 11 sites in IL, KY, OH, PA, and WV, with the VA site excluded from analysis because data were incomplete and the IN sites excluded because of uneven aged stand characteristics), sufficiency values and a PI_{GEN} value were calculated for each sampling location, and a mean PI_{GEN} was calculated for each site. Rodrigue had measured site index (SI) for the dominant species at each site, and converted that measured SI value to a 50-year white-oak site index ($SI50_{WO}$). PI_{GEN} values were regressed against $SI50_{WO}$ to test the validity of PI_{GEN} as a site-index indicator, and to define an SI_{50} predictive relationship.

The forest productivity of each of the current study's sampling sites was estimated by applying the General Model method to whole-soil values. For properties analyzed over the full 30 cm sampling depth (texture, bulk density) measured values were used as estimates of whole-soil values and to determine sufficiency levels. For properties analyzed separately for 0-10 cm 10-30 cm layers (pH), a whole-soil value was calculated assuming a depth of 78 cm (as per Andrews *et al.* 1992); the 0-10 cm value was considered as representative of 0–10 cm layer, the 10-30 cm value was considered as representative of soil properties extending from 10 – 78 cm, and a whole-soil value was calculated by considering component values as proportionate to representative depth (*i.e.,* with the 0-10 cm measurement contributing 12.8% to the whole-soil value). Sufficiency levels were determined using the whole-soil values.

Table 1. Sufficiency variables, and calculation methods, used to estimate a soil productivity index (PI_{GEN}) in the general model.

Sufficiency Variable	Soil Measure	Units	Sufficiency Calculation
S_{BD}	Bulk Density	g cm^{-3} (soil sized fragments)	If BD < 1.20, S_{BD} = 1.0 If BD 1.20-1.39, S_{BD} = 2.20 – 1.0 * BD If BD 1.40-1.70, S_{BD} = 4.53 – 2.67 * BD
S_P	Extractable P	mg/kg	If P > 9, S_P = 1.0 If P < 9, S_P = 0.29 + 0.32 * (ln P)
S_{EC}	Electrical conductivity	dS m^{-1} (1:5 soil:water ratio)	If EC < 0.05, S_{EC} = 1.0 If EC > 0.05, S_{EC} = 1.04211–0.84210*EC
S_{PH}	pH	Standard units	If pH < 5, S_{PH} = (-1) + 0.4 * pH If pH > 5 and < 6.5, S_{PH} = 1.0 If pH > 6.0, S_{PH} = 3.17 - 0.33 * pH
S_{CF}	Coarse Fragments	% of soil mass	If CF < 30, S_{CF} = 0.6 + 0.0133333* CF If CF > 30 and < 50%, S_{CF} = 1.0 If CF > 50, S_{CF} = 2.666667 – 0.03333 * CF

S_{TX}	Silt + Clay	% by mass of <2mm fragments	If (s+c) < 35, S_{TX} = 0.1 + 0.025791 * (s+c)
			If s+c > 35 and < 60%, S_{TX} = 1.0
			If (s+c) > 60, S_{TX} = 1.9 – 0.015 * (s+c)

S_{BS}	Base Saturation	%	If BS < 40, S_{BS} = 0.2 + 0.02 * BS If BS > 40, S_{BS} = 1.0

Estimate C Accumulation Potentials of Sampled Mine Sites:

C accumulation potentials for each mine site were estimated using equations derived by Amichev (2007) using data collected by Rodrigue (2001) as described by Burger *et al.* (2006):

$$\text{For pines: Eco\_C} = \text{Exp}(4.416+0.779*\text{SI/age}) \quad (5)$$

$$\text{For mixed stands: Eco\_C} = \text{Exp}(4.147+1.039*\text{SI/age}) \quad (6)$$

$$\text{For hardwoods: Eco\_C} = 219.455-3711.777*(1/\text{age}) \quad (7)$$

Where:

Eco_C = C accumulation as above- and below-ground biomass, litter, and soil organic materials on reforested mine sites (Mg C ha^{-1}).

SI = 50 year white-oak site index equivalent, expressed in meters (Because a number of different species were found growing on the pre-SMCRA sites, Amichev standardized all SI's to a 50-year white-oak equivalent, using Doolittle (1958)).

Age = Average age, in years, of the dominant and co-dominant trees.

Estimate C Accumulation Potentials and Significance of Post-SMCRA Mine Lands:

The total area of land disturbed and reclaimed by mining operations in eastern US states under SMCRA was estimated from SMCRA bond-release data obtained from US OSMRE. The distribution of soil and site conditions, and forest productivities, on the sampled mine sites were considered to be representative of the distribution of soil and site conditions on post-SMCRA mined areas. Considering these data, information gained through consultation with state and federal mining agency officials, the investigators' experience, and best professional judgment, the proportion of reclaimed mined areas potentially "available" for reforestation was estimated and applied to the SMCRA bond-release acreage totals to estimate the total acreage of post-SMCRA mined and reclaimed lands potentially "available" for reforestation. The total amount of C that could potentially be accumulated on these lands if reforested was estimated by applying equations (5), (6), and (7).

The potential significance of these lands' C accumulation potentials was estimated assuming lands would be reforested over a multiple-year period centered on the year 2010. Various measures of US coal combustion were developed as a basis for comparison.

Results and Discussion

Six mine sites were sampled in each of three states (OH, KY, and VA) and seven mines were sampled in WV (Fig. 2). The 25 sites yielded 225 sample locations (Table 2).

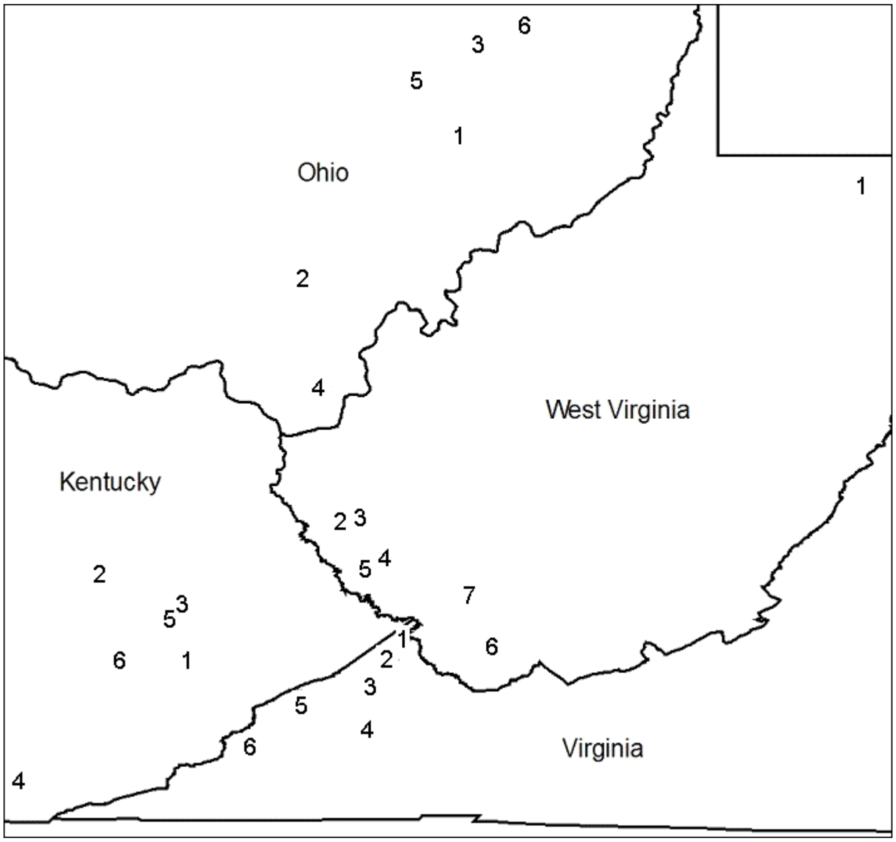

Figure 2. Mine site sampling locations. Numbers correspond with mine-site numbers on Table 2.

Table 2. Mine sites where soils and vegetation were sampled and characterized.

Mine Site	Number of Samples	County	Reclam.. Date[†]	Predominant Cover / Land Use
KY-1	5	Breathitt	1990	Abandoned grasses
KY-2	10	Wolfe	1996	Abandoned grasses
KY-3	10	Magoffin	1996	Abandoned grasses
KY-4	10	Knox	1990	Mixed grasses & scrub woody (black locust)
KY-5	3	Breathitt	1996	Reforested with pines
KY-6	10	Perry	1995	Abandoned grasses
OH-1	10	Muskingum	1987	Abandoned grasses
OH-2	9	Vinton	1990	Abandoned grasses
OH-3	10	Coshocton	2000	Abandoned grasses
OH-4	10	Gallia	1985	Wildlife Habitat
OH-5	9	Muskingum	1986	Wildlife Habitat
OH-6	6	Tuscawaras	1980	Grasses (Pastured until recently)
VA-1	8	Buchanan	1989	Mixed grasses & scrub woody (Black locust & red maple)
VA-2	9	Buchanan	1986	Forest - mixed hardwood & pines
VA-3	10	Buchanan	1988	Forest - mixed hardwood & pines
VA-4	10	Russell	1998	Mixed white pine & scrub woody (black locust)
VA-5	10	Dickenson	1995	Grasses (Pastured until recently)
VA-6	10	Wise	1998	Mixed grasses & scrub woody (autumn olive)
WV-1	10	Preston	1990	Abandoned grassland / scrub woody
WV-2	9	Mingo	1985	Scrub woody (mixture of planted and invasive hardwoods, black locust, and autumn olive.
WV-3	10	Logan	1994	Mixed grassland / scrub (black locust & autumn olive)
WV-4	8	Logan	1987	Mixed grasses & black locust.
WV-5	9	Logan	1995	Abandoned grasses
WV-6	10	McDowell	1984	Mixed grasses & scrub woody (autumn olive and other)
WV-7	10	Wyoming	1990	Scrub woody (black locust and other)

[†] Estimated average for sampling locations, based on available information as explained in text.

Vegetation

Vegetative cover characteristics were highly variable (Table 3). In order to compute mine site means, dominant vegetation species and communities recorded were grouped. The predominant planted-herbaceous species on all sites was tall fescue (*Schedonorus phoenix* (Scop.) Holub). Although sericea lespedeza (*Lespedeza cuneata* (Dum.-Cours.) G. Don) was present as a minor component of the vegetation mix on many sites, especially on VA, KY, and WV, it was rarely dominant or co-dominant. The highest percentage cover for planted herbaceous species was computed for OH, but no statistical differences occurred between states.

Numerous species – including choke berry (*Photinia sp.)*, greenbrier *(Smilax sp.)*, poison ivy (*Toxicodendron radicans* L.*)*, ladies lace (*Daucus carota* L.), sumac *(Rhus sp.)*, and Virginia creeper (*Parthenocissus quinquefolia* L.*)* -- were found on single or small numbers of sites and included in the "native herbaceous, shrubs, and vines" category, which represents non-forest-tree native species that were unlikely to have been planted and apparently invaded from surrounding terrain. Blackberry (*Rubus sp.)* was identified as a dominant or co-dominant shrub species at one or more sampling locations on 13 of the 25 sites. Golden rod (*Solidago sp.)*, ragweed (*Ambrosia sp.*), thistle (*Cirsium* sp.), and aster (*Aster sp.)* were the primary species recorded as dominant on the Ohio sites.

Table 3. Mine-site mean values of estimated percent cover provided by dominant vegetation types at sampling locations among mine sites, by state and for all mine sites sampled.

	- Planted Herbaceous -					- - - Native Woody - - -							
State - Site	Fescue	Other grasses	Lespedeza	Other herbaceous Legumes	Native herb, shrub, vine	Black locust	Red maple	Other native hardwood	Native softwood	Invasive	Other	Bare	Water
KY	36	2	12	16	4	10	0	3	8	2	-	7	-
OH	50	8	5	12	20	0	-	2	-	2	0	-	0
VA	20	-	13	3	9	7	10	7	17	12	0	2	-
WV	34	0	8	5	10	20	4	3	2	10	-	3	-
All	35	2	9	9	11	10	4	4	7	7	0	3	0

Few woody species were found on the OH mine sites. On the VA, WV, and KY mine sites, black locust (*Robinia pseudoacacia* L.) was the most common native woody species found, which is not surprising since it is widely planted. Black locust, however, does not produce high-quality timber when planted on mine sites. Red maple (*Acer rubrum* L.) was recorded commonly in WV and VA in patterns that appear to have occurred through natural invasion. Other native woody species with the potentials to form harvestable tree crops – including Virginia pine (*Pinus virginiana* P. Mill.), eastern white pine *(Pinus strobus* L.*)*, and hardwood species such as oaks (*Quercus sp.*) and tulip poplar (*Liriodendron tulipifera* L.*)* – were found to occur, with the greatest nominal frequencies in VA and WV, apparently in most cases due to reclamation plantings. Native woody species were recorded as occurring more commonly as dominant and co-dominant vegetative components at VA sites than at OH sites.

Autumn olive (*Elaeagnus umbellata* Thunb.) was the most common invasive species recorded, followed by muliflora rose *(Rosa multiflora* Thunb.). As a non-native species that is easily spread by birds, Autumn olive is classified as an "invasive" (Table 3) although some of its occurrences are likely to have originated as reclamation plantings. Autumn olive was recorded as a dominant or co-dominant component on all VA and WV sites, often at several locations. On sites where herbaceous biomass was sampled, amounts ranged from 506 to 1784 kg ha^{-1}, and the mean was 1136 kg ha^{-1} (Table 4). No statistical differences among states were noted. Herbaceous biomass was not collected at two Virginia sites where forest cover had closed canopy.

Table 4. Numbers of samples collected, mean values for herbaceous cover and soil physical properties at sampling locations by mine site, by state[†].

State -Site	Sam -ples	Herbaceous cover (kg ha^{-1})	Auger depth (cm)	Bulk Density (g cm^{-3})	Coarse Fragments (%)	Silt + Clay (% of soil-size frags)
KY	48	1217 ^{a}	27 ^{a}	1.13 ^{a}	56 ^{a}	62 ^{ab}
OH	54	1010 ^{a}	33 ^{a}	1.24 ^{a}	38 ^{b}	73 ^{a}
VA	57	1143 ^{a}	34 ^{a}	1.17 ^{a}	51 ^{a}	59 ^{ab}
WV	66	1140 ^{a}	25 ^{a}	1.26 ^{a}	54 ^{a}	53 ^{b}
All	225	1136	30	1.21	50	62

[†] State means followed by different letters are significantly different (ά = .05), as determined via Tukey's HSD test applied to site means.

Soil Properties:

Although soil properties varied widely among sampling sites, few significant differences were found (Tables 4 and 5). Auger penetration depth proved to be a difficult procedure to implement in a manner that yielded consistent results in the field. Site mean bulk densities of the soil-sized particles ranged from 0.93 to 1.54 g cm^{-3}, with a mean value for all sites of 1.21 g cm^{-3}, while site-mean coarse fragment contents ranged from 23 to 62% with a mean value of 50%. Silt + Clay (S+C) contents were nominally greatest in OH, an apparent result of that state's requirement that topsoils or soil-like topsoil substitute materials be used to construct a surface medium. Site mean pH values were generally in the range of 5 to 7, with only 4 sites (2 in KY, 1 each in VA and WV) having mean pHs below 5 and only two sites (both in OH) having mean pHs > 7 (Table 5). Measured mean EC values were generally low, relative to ECs typically found in fresh mine spoils, a likely result of the weathering that has occurred in these mine soils. The highest EC values occurred in association with low pH's (< 4.5), indicating a likelihood that continued pyrite weathering is the source of the salts and high EC. Base saturation was generally high at the sampling sites, with 15 of the 25 mine site means at greater than 90%, a likely result of base cations released from the formerly fresh mine soils via soil weathering.

Table 5. Mean (all but C and N) and median (C and N) values for soil chemical properties[†] at sampling locations by mine site, and mean values of mine site means by state and total.[‡].

State-Site	pH	EC (dS m^{-1})	CEC (meq /100 g)	BS (%)	P (mg kg^{-1})	C (Mg ha^{-1})	N (Mg ha^{-1})
KY	5.58 ^{a}	0.17 ^{a}	8.8 ^{a}	88 ^{a}	2.51 ^{a}	24 ^{a}	1.0 ^{b}
OH	6.49 ^{a}	0.05 ^{a}	15.1 ^{a}	96 ^{a}	4.28 ^{a}	29 ^{a}	1.8 ^{a}
VA	5.73 ^{a}	0.05 ^{a}	7.8 ^{a}	83 ^{a}	3.59 ^{a}	20 ^{a}	1.1 ^{b}
WV	5.58 ^{a}	0.03 ^{a}	6.8 ^{a}	86 ^{a}	3.22 ^{a}	28 ^{a}	1.2 ^{b}
All Sites	5.92	0.07	9.7	88	3.35	25	1.2

[†] Soil properties expressed for top 30 cm for C and N, and on a whole soil basis, assuming 78 cm depth for other properties listed.

[‡] State means followed by different letters are significantly different (ά = .05), as determined via Tukey's HSD test applied to site means for normally distributed variables and to site ranks for non-normally distributed variables (EC, CEC, and BS).

Extractable soil P was highly variable, with mine site means ranging from 1.5 to 6.4 mg/kg and values were well distributed throughout that range. Extractable P levels for the 10-30 cm depth samples at 18 of the 225 sampling locations were recorded as being less than the analytical detection limit, equivalent to 0.78 mg/kg; these values were set at the detection-limit-equivalent value for the purpose of calculating means. More than 50% of the detection-limited soil P values occurred in association with pH>7.

Individual mine sites were characterized for soil N and soil C accumulation using median (rather than mean) values due to the occurrence of a small number of very high soil values (5 values exceeded 80 Mg/ha, with the highest value at 256 Mg/ha) which we considered to be outliers; in some cases, these values were associated with observations of apparent coal among the coarse fragments, but apparent coal was also observed in some samples that did not exhibit very high soil C levels. The C measurements are total C and therefore include any carbonate or fossilized C that may have been present. However, we expect that carbonates were a minor to negligible component of the measured soil C values on most of these sites because carbonate strata are not common the central Appalachian coalfields; because EC values indicate that these minesoils were well weathered (the carbonate cements occurring as components of clastic rocks, are removed over time by weathering processes); and because only 4 of the 25 mine sites had mean pH values > 6.5. Soil C measurements also include whatever coal-C may be present as well as pedogenic C, our primary interest. Nitrogen also occurs as a component of coal and several high N values also occurred as apparent outliers, so N was handled similarly. Mine-site median soil C ranged from 10 to 56 Mg/ha, and mine-site median soil N ranged from 0.8 to 2.4 Mg/ha. Soil N occurred on Ohio sites in higher quantities than on other states' sites (p<.05), which may reflect the fact that Ohio requires topsoil replacement whereas use of topsoil-substitute materials (*i.e.*, rock overburden materials from rock layers originating from well below the surface) to construct surface soils is common in the other states.

Estimating Forest Productivities

Jones-model sufficiency values and productivity indices were estimated for each sampling site; sampling site productivity indices were calculated using equation (2), and averaged and transformed to $SI50_{wp}$ values (50 year site index for white pine) by mine site. Auger depth and S+C were interpreted to be the soil properties most limiting to forest productivity (with all-mine-site mean values of 0.66 and 0.67, respectively), according to the Jones model (Table 6).

Soil properties measured by Rodrigue (2001) on older mine sites were translated into sufficiency values and used to calculate PI_{GEN} values for each sampling site, and sampling site values were averaged to calculate a PI_{GEN} value for each mine site. Rodrigue had also estimated $SI50_{WO}$ (50-year site index for white oak) values for each site, based on measured growth rates of the dominant species.

The relationship between PI_{GEN}, estimated from Rodrigue's (2001) soil data, and $SI50_{WO}$ was found to be positive and statistically significant (p<.05) using Spearman correlation. An equation for estimating $SI50_{WO}$ as a function of PI_{GEN} was generated using .jmp software (SAS Institute, Cary NC):

$$Y = \Theta1 + (\Theta2 - \Theta1) / (1 + \exp(\Theta3 * (x - \Theta4))) \qquad (8)$$

where $\Theta1$ = function minimum value, $\Theta2$ = function maximum value, $\Theta3$ = negative of slope at inflection point, and $\Theta4$ = x value at inflection point. The equation was solved using the non-linear modeling component of the .jmp software by setting $\Theta1$ equal to zero and optimizing remaining parameters by minimizing residuals' sum-of-squares; parameter estimates generated by the software were Θ2 = 86.726242851, Θ3 = -23.62200379, and Θ4 = 0.6976016252 (Fig. 3).

Table 6. Mine site mean values of sufficiency values (S), the productivity index used to estimate site index using the Jones model (PI_{JONES}), and estimated 50 year site-index values calculated using the Jones Model ($SI50_{WP}$) with mine site means averaged by state and for all mine sites sampled.

State	S_{BD}	S_{AD}	S_{S+C}	S_{pH}	PI_{JONES}	$SI50_{WO}$
KY	0.89	0.62	0.66	0.75	0.758	25.8
OH	0.83	0.74	0.51	0.70	0.728	24.9
VA	0.84	0.69	0.70	0.86	0.772	26.2
WV	0.78	0.60	0.78	0.88	0.738	25.2
All Sites	0.83	0.66	0.67	0.80	0.749	25.5

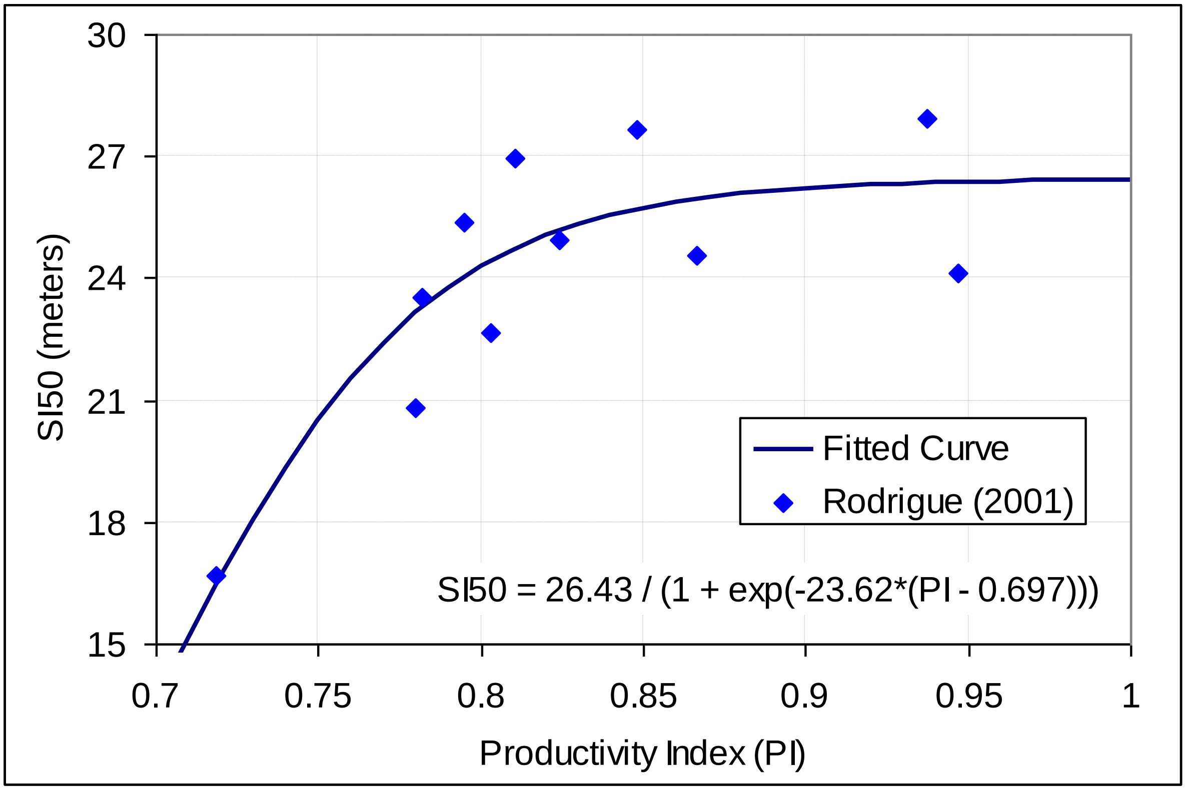

Figure 3. Data used for validation of the General Model.

Sufficiency values for each component of the General Model were estimated, summed, and used to calculate PI_{GEN} for each sampling location using equation 6; means for each sufficiency value and PI_{GEN} were calculated for each mine site, and mean mine-site values were calculated for each state and for all sites sampled. Using the General model, Extractable P was found to be the soil property that is most limiting to forest productivity (mean Sp = 0.63), while EC and BS were found to be least limiting, with mean sufficiencies of 0.97 and 0.99 respectively. Soil P and BS are indicators of soil nutrient levels. When considered together, these two factors suggest that lack of P, not the base cations (Ca^{++}, Mg^{++}, and K^{+}), tends to create soil fertility limitations to forest growth over time. Mean sufficiencies for the other 4 General Model parameters ranged from 0.80 to 0.88.

Mine-site mean $SI50_{WO}$ values estimated by applying the General Model's calibration equation (Fig. 3) to calculated PI_{GEN} values from ranged from 22.1 to 26.2 m (Table 6), while Jones-model estimated $SI50_{WO}$ values range from 19.9 to 30.0 m (Table 7). Mean values for $SI50_{WO}$ estimated using the two models, however, are quite similar (25.1 m for the General Model, 25.5 m for the Jones Model). Productivity indices and the SI50WOs generated (Fig. 4) generated by the two models exhibit highly-significant statistical relationships (p<.001) with one another.

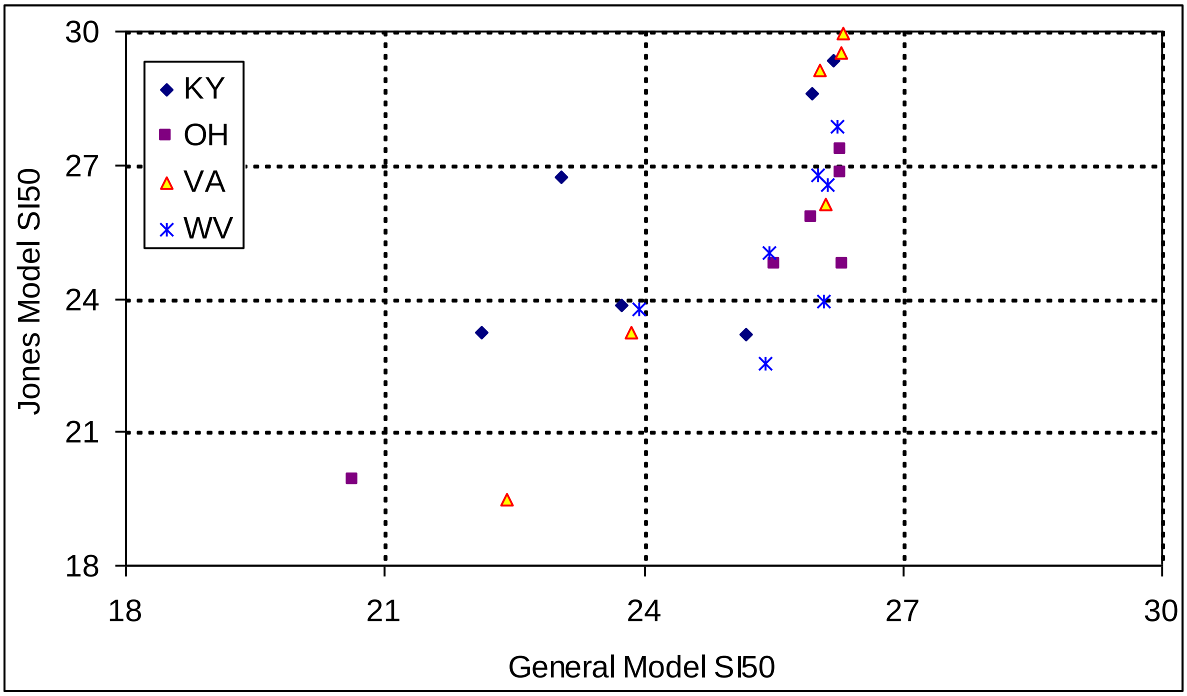

Figure 4. Relationship of the 50-year site indices (SI50s expressed in meters, below) for mine sites estimated by the Jones Model and the General Model.

Estimating Cumulative Ecosystem C Potentials of the Mined Land Resource Base:

Several assumptions were made in order to estimate the total C-accumulation potentials of the post-SMCRA mined land resource base:

Table 7. Mine site mean values of sufficiency values (S) and the productivity index used to estimate site index using the general model (PI_{GEN}), with mine site means averaged by state and for all mine sites sampled.

State	S_{BD}	S_{CF}	S_{S+C}	S_{pH}	S_{EC}	S_{BS}	S_P	PI_{GEN}	$SI50_{WO}$
KY	0.89	0.72	0.89	0.80	0.91	1.00	0.54	0.82	24.4
OH	0.83	0.92	0.79	0.84	0.99	1.00	0.72	0.87	25.2
VA	0.84	0.77	0.91	0.91	0.98	0.97	0.65	0.86	25.2
WV	0.78	0.78	0.92	0.93	1.00	0.98	0.62	0.86	25.6
All	0.83	0.80	0.88	0.87	0.97	0.99	0.63	0.85	25.1

Assumption 1: The forest productivities of mine sites sampled and characterized are representative of those which occur across eastern US. The four states where sampling sites were located accounted for 78% of the combined Phase III and recent (2001-2005) Phase I bond-released lands in eastern US (Table 8). The fact that few statistically-significant differences among states in soil properties, and no statistically significant differences among states in site index, were found provide no reason to stratify the analysis by state.

Table 8. Eastern US coal-mined land areas reclaimed under SMCRA, 1978-2005.[a]

State	Phase III Released	Phase I Released (2001-2005) - - - (hectares[b]) - - -	Total
E Ky[c]	247,176	26,094	273,269
MD	5,372	118	5,490
OH	74,167	9,495	83,661
PA	93,670	13,360	107,030
TN	14,962	2,946	17,907
VA	37,076	1,126	38,202
WV	93,686	11,674	105,360
Total	566,107	64,813	630,920

[a] including the interim SMCRA program. Source: US OSMRE "20th Anniversary of the Surface Mining Law" (http://www.osmre.gov/annivrep.htm) and annual reports to Congress.

[b] As reported by states to OSMRE; these figures overestimate total affected areas due to double-counting of areas that were both mined and re-mined under SMCRA.

[c] Estimated from total Kentucky areas, as proportionate to the east-west distribution of surface coal tonnage.

Assumption 2: The quantity of Eastern US mined lands that could be available for reforestation and sequestration is on the order of 300,000 ha. This estimate was derived assuming approximately ½ of lands mined and reclaimed under SMCRA could be made available for C sequestration. The 300,000 ha figure is slightly less than half of the total Phase 3 and recent Phase I (2001-2005) bond released acreage tallied by US Office of Surface Mining (Table 8). These acreages, however, include some double-counting due to remining of lands that were mined previously under SMCRA, but no estimate of such double-counted acreages is available. We are estimating that about 50% of available acreage could be made available under the right incentive structure considering several factors. First of all, some of the post-SMCRA mined lands are already in beneficial uses, such livestock grazing, and various forms of development. We are aware of no data to allow an estimate of such a quantity, but our experience indicates it to be very small, far less than 50%.

Second, some land owners may not wish to make their lands available for C sequestration even if additional incentives were offered. If mineral owners believe that future marketplace changes will make it profitable to mine such properties again, so as to extract coals that could not be exploited economically when past mining was occurring, most would consider potential returns from future mining as likely to far outweigh potential returns from reforestation and C sequestration. We would not expect a majority of landowners to fall into this category.

A third factor considered concerns the status of the vegetative communities on mine sites at present. Assuming soil properties are equally favorable, reforestation will be most feasible where mine sites are not occupied by invasive woody vegetation (such as the autumn olives that are proliferating in VA and WV mining areas) or by low-value species with poor timber-production and C-sequestration potentials that may have been planted after mining (such as black locust, which has been used commonly for reclamation in VA, WV, and KY). If such species are present and have advanced to the point where they would hinder reforestation success, they must be eliminated if the site is to be successfully reforested; this can only occur at some cost. About 2/3 of the cover provided by dominant and co-dominant vegetation types at sampling locations was provided by planted herbaceous species and native herbaceous species, vines, and shrubs, vegetative communities that we interpret as consistent with conditions necessary for successful reforestation. Although such species do accumulate C, and can accumulate it rapidly during the first 10-20 years after reclamation, those accumulations are generally not harvested and converted to sequestrable forms such as building products.

Assumption 3: Post-reforestation C accumulation on planted sites can be estimated using equations 5, 6, and 7. Carbon accumulations on post-SMCRA mined lands were estimated assuming rotation lengths of 30 years for pines and mixed pine-hardwood stands, and 60 years for hardwoods, as per Amichev (2007).

Carbon Accumulation on Post-SMCRA Mined Lands:

Application of equations 5. 6, and 7 using the above assumptions allows calculation of estimated average C accumulations over single rotations of 160, 152, and 158 Mg C ha^{-1} for pines, mixed pine-hardwood, and hardwoods, respectively (Table 9). These total accumulations correspond with C accumulation rates of 5.3, 5.1, and 2.6 Mg ha^{-1} yr^{-1}, respectively, for the three stand types (Table 10).

Table 9. Mean estimated C accumulation over a single rotation for three stand types for sampled mine sites with site indices estimated using the general model and the Jones model, and all-site averages of the two sets of SI estimates.

Stand Type	Rotation Length (years)	Jones Model	General Model	Average of Two Models
Pines	30	159	161	160
Mixed Pines /Hardwoods	30	151	154	152
Hardwoods	60	158	158	158

Table 10. Mean estimated C accumulation metrics for three stand types on sampled mine sites over a single rotation and assuming sampled sites are representative of 300,000 ha with potential for reforestation.

Stand Type	Pines	Mixed	Hardwoods
On Sampled Mine Sites:			
Over 1 Rotation (Mg C ha^{-1})	160	152	158
Rotation Length (yr)	30	30	60
Annual Rate (Mg C ha^{-1} yr^{-1})	5.3	5.1	2.6
Cumulative on 300,000 ha:			
Average Rates (Tg yr^{-1})	1.60	1.52	0.79
As proportions of US coal combustion C emissions[a]:			
2004 emissions	0.28%	0.27%	0.14%
2010 projected emissions	0.25%	0.24%	0.12%
2025 projected emissions	0.20%	0.19%	0.10%

[a] Emissions data from US EIA 2006b, Reference Case Table A-18.

The assumption that 300,000 ha could be reforested with an appropriate incentive structure over a relatively short time period allows extension of the above to estimate that the cumulative potential of the eastern US mined-land resource base to accumulate C if reforested is less than 2 Tg yr^{-1}, on average over an initial rotation. Assuming that pines and/or mixed stands would be targeted by any such incentive program because of their potential to accumulate C more rapidly than hardwoods, post-SMCRA mined lands cumulative potential to accumulate C is equivalent to about 0.2% of projected US combustion emissions from coal in 2025, the midpoint of a representative 30-year rotation beginning circa-2010 (Table 10). Coal consumption within the eastern mining states that were the subject of this research constituted about 23% of US coal consumption in 2005 (US EIA 2006a). Thus, the estimated potential of mined lands, if reforested with pines, to accumulate C is on the order of 1% of total projected coal-related emissions from these states.

The potential of reforested mine sites to accumulate C, as represented by these findings, should be considered as less than their potential to *sequester* C so as to offset energy-related C emissions. Two factors that have not been considered in generating these C-accumulation estimates are the *additionality* of potential reforested-mine-site C accumulations (*i.e.*, the amount of accumulated C over and above that which would occur in the absence of active reforestation), and proportion of accumulated C that could be converted to climate-neutral forms, such as long-term soil C, wood-products placed in long-term non-biodegradable uses, and renewable fuels used to offset fossil-fuel utilization.

Summary and Conclusions

Eastern US lands that have been mined for coal and reclaimed under the Surface Mining Control and Reclamation Act constitute a significant land resource. Large proportions of eastern US coal-mined lands have not been reforested and are currently not under active management for any economically valued purpose. We investigated the potential for these lands to accumulate C if actively reforested. Should such reforestation occur, results would also include ancillary benefits as environmental services, such as enhanced watershed protection, and timber products.

Soil properties on these mine sites appear to be generally well-suited for reforestation. The mean 50-year site index for white oak on 25 mine sites identified through a random selection procedure was estimated at about 25 meters using two different methods, a level that would be considered as better-than-average on natural soils occurring in most eastern US areas mined for coal. Soil compaction was not found to be a major limiting factor on most sites. Low amounts of plant-available phosphorous, a soil property that would be easily ameliorated during a reforestation procedure through fertilization, was the property that our study found to be most limiting to reforestation potentials.

One major site factor that occurs commonly, was not included in the soil productivity models, and that can be expected to hinder reforestation of sites where it occurs is the proliferation of low-value woody species with little potential to produce marketable timber – especially black locust (which has been planted by many mining operations under SMCRA) and autumn olive (a non-native invasive species that was formerly planted by mining operations and is proliferating as its seed are spread by birds and by other means). When mine sites become occupied by such species in advanced growth stages, that woody biomass becomes a barrier to successful reforestation. Their presence acts as a physical obstacle to equipment operations, and, unless removed prior to planting, their rapid growth can be expected to influence negatively planted seedlings growth and survival. When these species reach advanced stages, the cost of removal can render reforestation investments unprofitable. As time passes, it is likely that many mine sites which are not currently occupied by such species in advanced growth stages will become so occupied, and such sites' potential for reforestation will decline as a direct result.

If on the order of 50% of the lands mined for coal and reclaimed under SMCRA in the eastern US were to be reforested, estimated rates of C accumulation on such sites are in the range of 0.8 – 1.6 Tg C yr^{-1}, on the order of 0.2% of US C emissions from coal combustion.

Although potential C accumulation and sequestration quantities are not great relative to potential national needs (should energy-related C-emissions offsets become a requirement at some future date), these lands are available and are unused for other economically valued purposes, while many possess soil and site properties that are well-suited to reforestation. As time passes, their collective potential for reforestation can be expected to decline due to the influence of continued proliferation and growth of low-value woody species with minimal C sequestration potentials, including non-native invasives that were formerly planted commonly during reclamation under SMCRA on coal surface mines.

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