Carbon Sequestration on Surface Mine Lands

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Abstract

Carbon (C) emissions resulting from power generation has been implicated as a contributor to global warming. To offset increases in atmospheric CO_2 we must better exploit the natural capacity of terrestrial ecosystems to accumulate carbon. Lands exploited for coal production may offer the potential for storage of significant amounts of C on sites that are currently disturbed and underutilized. Evidence from sites reclaimed without excessive site compaction demonstrates the great potential for forest production on post-mining lands. Under optimal conditions forest production on reclaimed mines can exceed that of unmined sites. More typically, however, mine reclamation carried out in accordance with the Surface Mining Control and Reclamation Act of 1977 (SMCRA), forfeits the potential to accumulate C on surface mined lands. Mine spoil handling, placement and compaction, result in shallow soils that are low in nutrients and organic material. Forest establishment and growth are limited by the xeric, nutrient poor conditions. Societal pressure to allow recovery of Southern Appalachian forest ecosystems and to realize potential benefits of carbon storage will require greater understanding of controls on forest production and carbon accumulation on reclaimed mined lands. To address these concerns across a broad gradient of climatic and post-mining conditions, we are initiating a research project at three sites that encompass Kentucky's eastern and western Coalfields Regions. Research will assess the effect of various tree species planted in pure and mixed species stands and spoil material type and rooting volume on carbon capture, release and storage in aboveground and belowground pools. The species and site preparation treatments will provide a gradient of biomass and litter production that will control carbon accumulation. Findings from our study will help improve predictions of carbon sequestration and will help to guide reclamation that aims to maximize carbon capture on reclaimed mine ecosystems.

Overview

Carbon (C) sequestration is defined simply; it is "the process of increasing the carbon content of a carbon pool other than the atmosphere" (Intergovernmental Panel on Climate Change [IPCC], 2000). Projected climate change resulting from the increase in atmospheric carbon dioxide (CO_2) has given rise to various strategies designed to store additional carbon in terrestrial ecosystems (IPCC 1991, 2000). Efforts to remove C from the atmosphere and sequester it within terrestrial ecosystems are intended to complement reductions in net energy use accomplished by improving the efficiency of new and existing power plants and by adopting energy conservation plans (Zilberman and Sunding, 2001).

Land management options designed to increase terrestrial C inventories include both improving present land use practices as well as land use conversion (Lal et al. 1998). Because of the current spatial extent of forest, crop and grazing land there is potential to build terrestrial C stocks through improved management. Fertilization, thinning, and elongation of rotation lengths are strategies for increasing C storage on productive forest lands (Winjum and Schroeder, 1997; Nabuurs et al. 1999). On agricultural lands, improved management options include establishing highly productive deep-rooted pasture grasses (Fisher et al. 1994), adoption of conservation tillage (Kern and Johnson, 1993), and sewage sludge or animal manure amendment (Lal et al. 1998). Land conversion options considered as globally significant strategies for increasing terrestrial C inventories include establishing conservation reserves on agricultural lands, reforesting agricultural land, and rehabilitating degraded lands, such as contaminated industrial areas or mine lands (IPCC, 2000; Nabuurs et al. 1999).

In the Appalachian region, where the majority of the 2.4 million hectares disturbed by US coal mining resides (Zeleznik and Skousen, 1996), carbon sequestration complements traditional reclamation objectives. Globally, C accumulation rates on degraded lands have been estimated at 0.3 Mg C ha^{-1} yr^{-1} (Nabuurs et al. 1999; IPCC, 2000). **Our objective is to assess the potential of C sequestration on mine lands in the Southern Appalachian Coalfield region. We will first discuss the C storage within temperate forest ecosystems, then review forest production and soil C accumulation on mine lands. This review will identify research priorities aimed at maximizing forest C sequestration on reclaimed minelands.**

Forest Carbon Inventory

Carbon gained through plant photosynthesis is initially partitioned within various aboveground and belowground compartments and then transformed from live to dead organic matter. Carbon represents roughly one half the mass of live biomass and detrital organic matter pools. In temperate forest ecosystems, aboveground detritus includes leaf, coarse woody material (branch and logs) in various stages of decomposition, as well as standing snags. Belowground C pools include both live and dead roots and soil organic matter.

Globally, soil holds nearly three times the amount of C contained within standing vegetation and twice that residing in the atmosphere (Schlesinger, 1991). In US forests, mineral soil contains about 60% of the ecosystem C stock with an additional 10% stored within the forest floor (Birdsey et al. 1993). Trees and large roots account for the final 30% of the forest C capital.

The long-term fate of sequestered C depends upon residence times of soil C pools and conservation or consumption of aboveground forest biomass. Forest-derived C may be stored within live stem biomass for 10s to 100s of years. Harvest followed by biomass combustion returns C to the atmosphere; harvest and incorporation of tree biomass into wood products represents a significant reserve of terrestrial C (Nabuurs et al. 1999). In the temperate region, 40% of the C is gained during a 25-year forest plantation rotation (23 Mg C ha^{-1}) remains stored within solid wood products (Winjum and Schroeder, 1997). The residence time of C stored belowground can vary from <1 year to centuries (Parton et al. 1987). Various soil C components differ with respect to their chemical resistance to microbial decay and their physical protection within soil aggregates.

On average, deciduous and evergreen temperate forest vegetation contain 135 and 160 Mg C ha^{-1} with about 130 Mg C ha^{-1} stored in soil organic matter (Houghton, 1995). In a survey of deciduous and coniferous forests of the warm and cold temperate regions, Vogt and colleagues (1995) found that living biomass accounted for 42 to 62% of the total ecosystem C. Soil organic matter contained 33 to 50% of the forest C. Mature mixed-oak forests in eastern Tennessee contain a total of 270 to 330 Mg C ha^{-1} (Johnson and Todd, 1998). Of the total C reserve, aboveground vegetation and soil contained 73 and 23%, respectively; forest floor contains 3 to 20 % of the ecosystem C stock (Vogt et al. 1995; Johnson and Todd, 1998; Richter et al. 1999). In the warm temperate zone, deciduous forests contained about 50% more total C than coniferous forests, although forest floor C was 3-fold greater beneath coniferous forests (Vogt et al. 1995). In coniferous and deciduous forest, woody debris contains 30 to 50% the amount of C found in undisturbed live biomass (Harmon et al. 2001).

The temperate forest region is considered to have great potential as a sink of atmospheric C (Kauppi et al. 1992; Birdsey et al. 1993). Due to extensive agricultural abandonment in the eastern United States and the significant forest biomass that has developed, C stored in US forest ecosystems has increased by 38% since 1952 (Birdsey et al. 1993). Based on a conservative 50 Mg C ha^{-1} aboveground biomass C stock, the net forest C increment of 15 European nations (temperate and boreal region) is estimated at 1.8 Mg C ha^{-1} yr^{-1} (Liski et al. 2000). For temperate forests, biomass C increment is estimated at 4.1 Mg C ha^{-1} yr^{-1} based on combined aboveground and belowground (64 Mg C ha^{-1}) biomass measures (Winjum and Schroeder, 1997).

Forests regenerating following whole-tree harvesting in eastern Tennessee added 26 Mg C ha^{-1} to aboveground biomass and 27 Mg C ha^{-1} to mineral soil reserves during 15 years (Johnson and Todd, 1998). A century-old reference forest at the same site added 60 and 12 Mg C ha^{-1} to forest biomass and soil during the same period. For these Tennessee sites, vegetation C stocks increased by 1.7-4.0 Mg C ha^{-1} yr^{-1}, while the net rate of soil C increase was 0.8-1.8 Mg C ha^{-1} yr^{-1}. On the coastal plain of South Carolina, Richter and colleagues tracked the changes in C inventory over 4 decades following conversion of row cropping to a loblolly pine (*Pinus taeda*) plantation (Richter et al. 1999). The pine ecosystem accumulated 180 Mg C ha^{-1} during that period; annual tree, forest floor and mineral soil (0-30 cm) gained 4.26, 0.94, and 0.04 Mg C ha^{-1} yr^{-1}, respectively. Forest biomass accounted for 80% of added C inventory, while forest floor and mineral soil contributed 20% and <1%.

Forest Production on Mine lands

Accumulation of significant C stocks on mine lands depends upon the capacity of reclaimed mine soils to support forest production. Evidence from a number of North American sites demonstrates that under adequate conditions, mineland forest production can meet or exceed that of unmined lands (Torbert and Burger, 2000). Based on the mean height growth of a broad selection of species growing on Midwestern or Appalachian mine lands, we estimate 45 cm of annual height increment during at least the first 2 decades (Table 1; Fig. 1). After a decade, mean tree height could therefore approach 5 m. Across 34 reclaimed mine sites in southwestern Virginia, white pine (*Pinus strobus*) tree heights ranged from 0.9 to 6.9 m after a 10 years (Torbert et al. 1988). On average quality mine soils, Burger and Torbert (1997) project similar height growth for white pine on mined and unmined sites at age 25. On deeper, high-quality mine soils, white pine may attain 21 m at 25 years and reach 30 m after 50 years (Burger and Torbert, 1997).

Survival and growth of a wide array of species have been evaluated as candidates for mineland reforestation (Larson and Vimmerstedt, 1983; Wade et al. 1985; Ashby, 1997). In 1946 and 1947, the U.S. Forest Service established species trials on eastern and southeastern Ohio surface mineland (Larson and Vimmerstedt, 1983). White and green ash (*Fraxinus americana* and *F. pennsylvanica*) had the best survival of 15 species tested; both had greater than 50% survival after 30 years. The fastest growing species, yellow poplar (*Liriodendron tulipifera*), white ash and white pine, all surpassed 10 m height at age 30. In an associated evaluation of direct seeding, bur oak (*Quercus macrocarpa*) had good survival (37%) and comparable height growth as white ash and black locust (*Robinia pseudoacacia*; 11 m). White pine and white ash also excel during the early years of growth on mine soils (Graves 2001, *unpublished data*). On uncompacted spoil in eastern Kentucky, these species reach 1.5 and 1.3 m within 5 years.

Mixed-species plantings of nitrogen-fixing tree or shrub species with hardwood crop trees are commonly promoted for mine land revegetation (Ashby et al. 1985). After a decade, yellow poplar and green ash heights were 3-fold greater when underplanted within black locust stands than when established in pure stands in old agricultural fields (Finn, 1953). On spoil banks, underplanted hardwoods grew better and had greater foliar nitrogen content when planted beneath black locust compared to shortleaf pine (*Pinus echinata*; Finn, 1953). When black locust is seeded or planted simultaneously with crop tree species, competition may reduce crop tree performance (Larson and Vimmerstedt, 1983). Underplanting beneath declining black locust stand or interplanting with controlled densities of black locust seedlings appear have potential for increased crop tree growth (Torbert and Burger, 2000).

Mine Spoil Conditions and Forest Productivity

Productivity varies greatly across mine lands and reclamation activities can either facilitate or hinder their utility for forest growth or C sequestration. Public Law 95-87, the Surface Mine Reclamation Act (SMCRA) was established in 1977 to regulate environmental impacts of surface mining and direct mine reclamation activities. The act requires that mined lands be returned to their approximate origin contour. The extensive spoil compaction needed to recontour mined lands has severely reduced tree growth on mines reclaimed since 1977 (Torbert and Burger, 2000).

Recent work in Kentucky (Graves et al. 2000) and elsewhere in the region has demonstrated that spoil compaction has a severe negative impact on tree growth (Fig. 2). After 5 years of stand development, trees growing on compacted soil grew only one-third as tall as those growing on loose spoils. While the negative effect of spoil compaction on forest growth has been adequately documented for plantations established since 1977 (Torbert and Burger, 1994; Ashby, 1997; Graves et al. 2000), similar conclusions were reached on plantations established much earlier (Listrom, 1952; Larson and Vimmerstedt, 1983).

The physical limitations on mine soils may not affect all species equally. On Ohio mines spoils, white pine and yellow poplar height was reduced by 24 and 60% respectively, after 30 years on compacted compared to uncompacted spoils (Larson and Vimmerstedt, 1983); in contrast, neither the height or diameter of white ash or black locust was altered by spoil compaction. After 5 years of growth on eastern Kentucky reclaimed mine lands, spoil compaction reduced the mean height of 7 different species by 63%; white ash height was reduced the least (50%) and white pine the most (85%) on compacted sites (Graves 2001, *unpublished data*).

Forest soils of the Appalachian region naturally have high rock content. The physical limitations to forest growth on reclaimed mines result from spoil compaction in conjunction with the high rock content of mine spoils (Ashby et al. 1984). These conditions reduce tree growth by forming layers that restrict downward penetration of roots, and alter drainage and water holding capacity within the rooting zone (Pedersen et al. 1980; Bussler et al. 1984; Bell et al. 1994). Coarse-texture soils formed from sandstone spoil materials may contribute to the xeric condition of some reclaimed areas (Vimmerstedt et al. 1989), although well-drained sandstone soils have been shown to support greater biomass production than finer-texture siltstone-derived spoils (Roberts et al. 1988; Torbert et al. 1990).

The physical impediments on compacted minesoils truncate the volume of soil available for root expansion and limit forest growth. The reduced volume of fine materials directly alters both water and nutrient availability. Effects of limited effective root volume and spoil compaction (Fig. 2), increase as trees fully occupy belowground resources. During initial establishment on western Virginia mine land, white pine height increment was unaffected by spoil depth (Torbert et al. 1988). From years 6 to 10, white pine height increment was well predicted by rooting depth.

The composition of spoil materials determines both chemical and physical properties of resulting mine soils (Jenny, 1941; Sobek et al. 2000). The original composition of mine parent materials therefore regulate both aboveground and belowground biomass production (Larson and Vimmerstedt, 1983; Preve et al. 1984; Torbert et al. 1990) as well as the capacity of mine soils to sequester C. In eastern Ohio, calcareous spoils form compact clay soils, and acidic shale and sandstone spoils form less-compact soils (Larson and Vimmerstedt, 1983). Survival for a variety of species was greater on calcareous spoil (37%) compared to non-calcareous spoil (23%), although height growth of yellow poplar, white pine, and various oak species was greater on non-calcareous spoils. In western Virginia, white pine volume production was 4-fold greater on slightly acidic weathered sandstone spoils compared to alkaline siltstone (Tobert et al. 1990).

Carbon Accretion in Mine Soils

Since the C content of spoil material is typically very low compared to undisturbed surface soils (Bussler et al. 1984), the potential to increase the C capital of reclaimed mine soils should be significant (IPPC, 2000). The net rate of carbon gain following conversion of severely degraded land to productive agricultural or forest land has been conservatively estimated at 0.25 Mg C ha^{-1} yr^{-1} (Lal and Bruce, 1999). Rates ranging from 0.2 to 2 Mg C ha^{-1} yr^{-1} are used to predict the affect of reclaiming mine land in Europe and the United States (Nabuurs et al. 1999; IPCC, 2000).

To provide an estimate of soil C accumulation across a wide variety of mine conditions we reviewed 7 studies that quantified soil C within mine spoils (Table 2; Fig. 3). This chronosequence approach tracks C accumulation in spoils from coal and other types of surface mining over a century of soil formation. Each study included spoils from 1 to 6 individual sites. The published soil C concentrations (%) were transformed into C stocks (Mg C ha^{-1}) for the upper 10 and upper 50 cm of mineral soil to allow comparison between studies. When available, site specific bulk densities were used; otherwise a conservative multiplier of 1.1 Mg m^{-3} was used to convert C concentration to an estimate of C mass.

The C stock within the upper 10 and 50 cm of mineral soil ranged from 3-33 and 17-82 Mg C ha^{-1}, respectively. The top 10-cm contained 44% of the C capital, but ranged from 23 to 73%; the lower 40-cm contained 56% of the C in the upper half meter of soil. Across this selection of studies, soil C is increasing by about 0.7 Mg C ha^{-1} yr^{-1} in the upper 50 cm of mineral soil (Fig. 3). After 100 years of soil formation on loess-derived spoils in Iowa, the soil C stock of the upper 10 and 50 cm were 26 and 82 Mg C ha^{-1}, respectively (Hallberg et al. 1978). During 30 to 40 years of development, C increased by 0.5 and 1.4 Mg ha^{-1} yr^{-1} in the upper 10 and 100 cm of sandy spoils in southern Saskatchewan (Anderson, 1977). Across a chronosequence of 15 Montana surface mine sites, the C content of the surface horizon (0-10 cm) recovered to undisturbed levels within 30 years of reclamation (Schafer et al. 1980). On 6 Illinois coal mine spoils spanning from 5 to 64 years in age, soil C increased by 0.1 and 0.3 Mg ha^{-1} yr^{-1} in the upper 10 cm and 50 cm (Thomas and Jansen, 1985).

Forest species alter rates of both mineral soil and forest floor C accretion. On coal spoils in southern Ohio, 4.1 Mg C ha^{-1} accumulated within forest floor beneath various forest species during a 30-year period (Vimmerstedt et al. 1989). The litter layer of white pine contained the greatest mass of C (7.8 Mg C ha^{-1}), surpassing the forest floor C beneath black locust, yellow poplar, and white ash 2- to 4-fold. Overall, C accumulated within forest floor by 0.2 Mg ha^{-1} yr^{-1}. As a result of inhibition of soil microbial and soil faunal decomposition rates, stands developed on acid spoil materials (pH < 4) supported thicker forest floor layers than either neutral or calcareous spoils. Mature mixed Southern Appalachian hardwood forests (80-100 year-old) contain 7-10 Mg C ha^{-1} (Thompson and Kolka, 2001, *unpublished data*; Johnson and Todd, 1998).

Spoil composition influences C sequestration both through the link between spoil type and aboveground or belowground biomass production and by the affinity of the mine spoil to stablize C inputs into slowly cycling organic matter pools. Spoil acidity and metal levels will control microbially-mediated nutrient transformations and litter decomposition (Tate 1985; Vimmerstedt et al. 1989). The content (Parton et al. 1987) and mineralogy (Motavalli et al. 1994) of clay in mine spoils will control belowground C storage either by formation of chemically recalcitrant organo-mineral complexes or through physical protection within soil aggregates (Golchin et al. 1994).

Proposed Research

Based on the literature review it is apparent that several factors influence C sequestration on reclaimed mine lands. Factors that will influence aboveground and belowground forest productivity and C accumulation in mine soils include tree species, the presence of N-fixers, spoil depth, spoil compaction level and type or source of spoil. Previous studies in Kentucky and West Virginia show that highly compacted soils result in poor establishment and growth (Graves et al., 2000; Torbert and Burger, 1994), leading to little C sequestration potential for post-SMCRA lands unless they are decompacted. Although the literature has shown that species, spoil depth, and spoil source all influence tree productivity (Zeleznik and Skousen, 1996; Ashby et al. 1984; Barth and Martin, 1984; Preve et al., 1984), no studies have assessed these factors in relationship to C sequestration on mine lands.

Tree species will vary in the amount of aboveground production, litter quantity inputs, litter quality inputs and root production (Figure 4). Those differences among species affect decomposition rate, soil mineralization and ultimately soil C storage. Conversely, differences in spoil depth and spoil type affect soil physical and chemical properties, rooting volume and soil moisture which ultimately affects aboveground production (Figure 4). The species effect is seen from the tree to the soil (i.e. litter controlled) while the spoil effect is seen from the soil to the tree (i.e. substrate controlled).

Study Objectives

It is with this review of previous work and considering the importance of understanding both the effects of species and spoil type and handling on C sequestration we propose three studies with the following objectives:

1) A comparison of tree species including monotypic and mixed species with and without an N-fixing species.
2) A comparison varying the depth of spoil material.
3) A comparison of various spoil types.

Study Hypotheses

1) Because of differences in growth rate and litter quality among species we expect that certain tree species will be better ecosystem C accumulators than other species and that the mixed species treatment will produce a more diverse C litter pool subsequently affecting forest floor and soil accumulation. We also hypothesize that the addition of an N-fixing species will increase growth, forest floor inputs and soil C storage.
2) Increasing spoil depth will enhance rooting volume and total fines thereby increasing aboveground and belowground production and soil accumulation of C.

3) Spoil source chemistry and nutrient availability will alter aboveground and belowground forest production and soil accumulation of C.

Site Locations

The study will take place in three distinct mining regions in Kentucky's eastern and western coalfields regions. Specific mining sites will be located in southeastern Kentucky near the West Virginia border, in southeastern Kentucky near Hazard and in western Kentucky (Figure 5).

Forest Species Effects on Mine Land C Sequestration

Tree species selections are intended to provide a gradient of tree growth and litter quality. Candidate species include white ash, yellow poplar, and white pine although others are still being considered. Seedlings of each species will be planted in replicated plots on leveled loose-dumped spoil across all three sites (Figure 5). Spoil will be graded to a minimum depth of 3 m. The reforestation species will be established in both pure stands and in mixed-species plantings with the N-fixer, black locust. To control potential competition, black locust will be interplanted rather than direct seeded. Plots will be randomly located within an individual study block (Figure 6). Tree spacing, rate of black locust planting, plot size and number of replicates are still to be determined.

Spoil Depth Effects on C Sequestration

On a series of replicated randomized plots at each site (Figure 5) we will vary leveled loose-dumped spoil depth with three treatments of spoil depth considered. Tentative depths are 0.5, 1.0, and 3.0 m. Tree spacing, black locust planting rate, replicates and plot size will be identical to the previous study.

Spoil Mineralogy Effects on C Sequestration

At each site we will identify spoil types that vary in chemistry, mineralogy and possibly fragment size fractions. Sites in eastern Kentucky are dominated by acid sandstones and circumneutral shales. Sites in western Kentucky are dominated by circumneutral shales and siltstones. We plan to work with the mining operators to isolate the dominant geologic strata at a particular site and loose dump those materials separately. As in the previous study, spoil depth will be a minimum of 3 m. Tree spacing, black locust planting rate, replicates and plot size will be identical to the previous studies. Blocks will be composed of similar spoil with replicates within blocks.

Methods

The methods are designed to measure treatment effects on aboveground and belowground C and nitrogen (N) pools and fluxes for the individual studies (Figure 7). It is critical to assess N cycling because of the influence N has on C cycling through litter quality inputs and soil development. Because the C cycle will be measured in each study, methods will be similar among studies. All sites will be instrumented with a weather station that will measure precipitation volume, temperature, relative humidity, wind speed and direction and solar radiation. The weather station will be centrally located among plots within each site.

Seedling height and diameter will be measured at planting and on annual basis for the duration of the project (a minimum of five years). Notes will be taken on seedling health, vigor, growth form and level of herbivory. Aboveground seedling biomass production will be estimated with allometric equations developed for individual species. Plots will be planted with enough seedlings so that some trees can be sacrificed for the analysis of C and N in stems, branches and roots. Clip plots will be used to measure herbaceous production with subsamples used to determine total C and N.

Litterfall biomass will be measured annually with litterfall traps. Forest floor biomass will also be measured annually as it develops over time. Litter and forest floor samples will be periodically analyzed for total C and N. Litter-bags will be used to measure litter decomposition rates for individual species and for the various combinations of species.

Soil characterization for chemical and physical properties and mineralogical composition will be conducted prior to implementing treatments and periodically throughout the duration of each study. Soil C and N will be measured on each plot prior to implementing treatments and once per year for the duration of each study. Soil C and N will be measured on the bulk soil as well as on the aggregate level to determine the extent that C is being physically protected as the soils develop. Root biomass will be measured with sequential soil coring over an annual cycle. Root turnover rates are extremely difficult to quantify and will not be conducted in these studies. With sequential root biomass measures we will get an estimate of overall root production over time.

Carbon dioxide efflux resulting from C mineralization in the soil will be measured seasonally on each plot with a portable infared gas analyzer. *In situ* incubations will be used to assess N mineralization rates within treatments. Soil C mineralization includes CO_2 effluxes from both root and microbial respiration. Greenhouse studies using spoil with and without plants (roots) will be used to separate the influence of roots and microbial communities on field CO_2 efflux rates.

Bulk precipitation collectors will be used to collect incoming precipitation and dry deposition for analysis of total organic carbon (TOC). Suction-cup samplers placed below the rooting depth will be used to sample soil water for C (TOC) leaching from the system. Time domain reflectometry will be used to measure soil moisture at various depths to both characterize soil moisture conditions within plots and to allow us to calculate water flux through the soil profile.

Expected Outcomes

Considering the low C status of newly mined sites, we expect that considerable gains will be seen in both aboveground and belowground C storage over a relatively short time period and that tree species, depth of spoil and type of spoil will control the rate of C accumulation. Our study results will not only enhance our understanding of C cycling in mined landscapes but also add to knowledge base from which reclamation specialists draw from when planning future reclamations. Considering the potential for mine lands to sequester C to offset rising rates of CO_2 in the atmosphere, we anticipate that our results will contribute to the ongoing justification to change current mine reclamation regulations and perceptions to allow loose dumped material and forest establishment.

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Table 1. Tree height on reforested mine lands in the Appalachian and midwestern regions.

Height (m)	Mean	Maximum	Minimum	# Species	Reference and Comments
Age					
50	24.2	30.5	18	1	Burger and Torbert, 1997
25	17	21	14		Mean, max & min correspond to 61, 109 & 31 cm spoil depth
30	9.1	11.9	6.1	9	Larson and Vimmerstedt, 1983
18	5.9	11.7	2.5	19	Wade et al. 1985
10	2.5	6.9	0.9	1	Torbert et al. 1988 Max tree ht when interplanted with black locust
5	1.7	1.9	1.7	1	Torbert et al. 1995 White pine growing across a range of rooting depth (20-100 cm)
2	0.2	0.5	0.1	3	Schoenholtz and Burger, 1984
1	0.1	0.2	0.1		Fertilizer + Herbicide increased growth

* 50 year white pine site index projected from year 10 growth

Table 2. Spoil characteristics for study sites included in review of C accumulation on mine lands.

Study	Spoil Age	Spoil / Mine Type	Surface pH	Location	Dominant Vegetation	Citation
1	42,31,30,28	Glacial Till	7.2	Saskatchewan	Mid- & shortgrass prairie	Anderson 1977
2	100	Loess	5.9-6.3	Iowa	Tallgrass prairie	Hallberg et al. 1978
3	50, 9	Coal	7-8	Montana	Mid- & shortgrass prairie	Schafer et al. 1980
4	50, 30, 15	Kaolin	5.5-6.4	Georgia	Mixed pine & hardwoods	Perkins and Troth, 1981
5	64,55,50,30,10,5	Coal	5.4-7.6	Illionois	Mixed hardwood & grasses	Thomas and Jansen, 1985
6*	25	Coal	4.8-5.0	West Virginia	not reported	Thurman and Sencindiver, 1986
7*	3, 2, 1	Coal	4.3-5.7	Spain	Improved pasture	Gonzalez-Sangregorio et al. 1991

* Included in 0-10 cm plot and calculations only

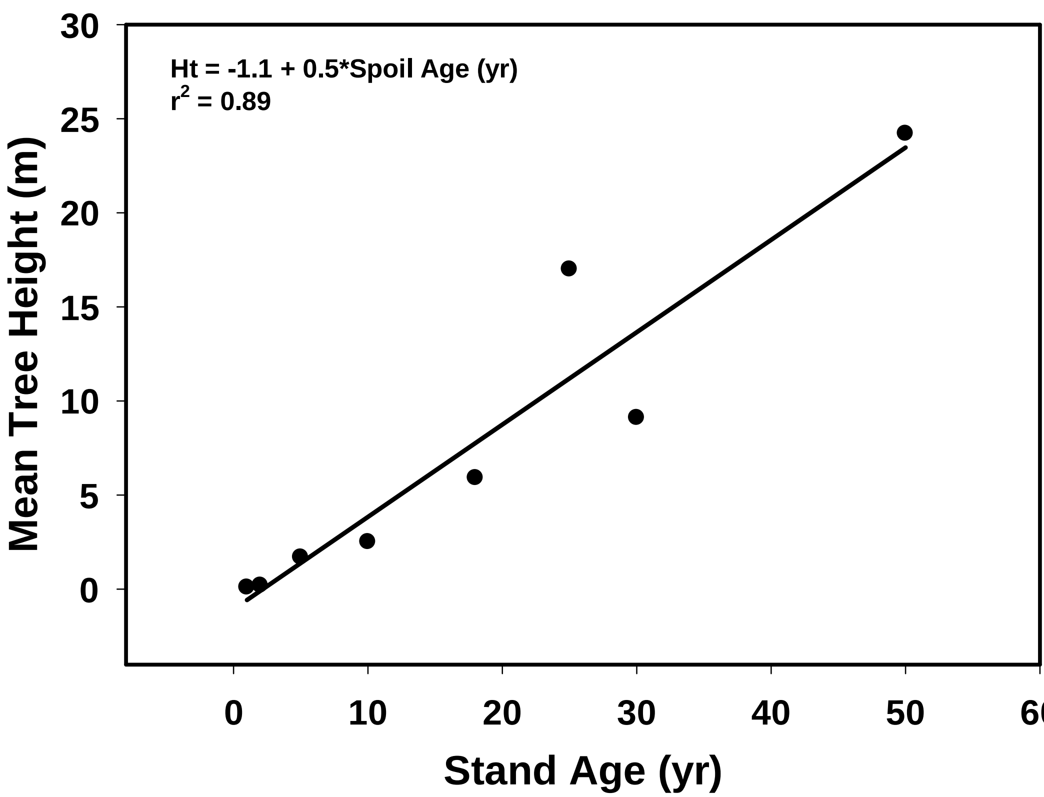

Fig. 1 Tree height across a gradient of spoil ages at reclaimed sites in the midwestern and Appalachian US.

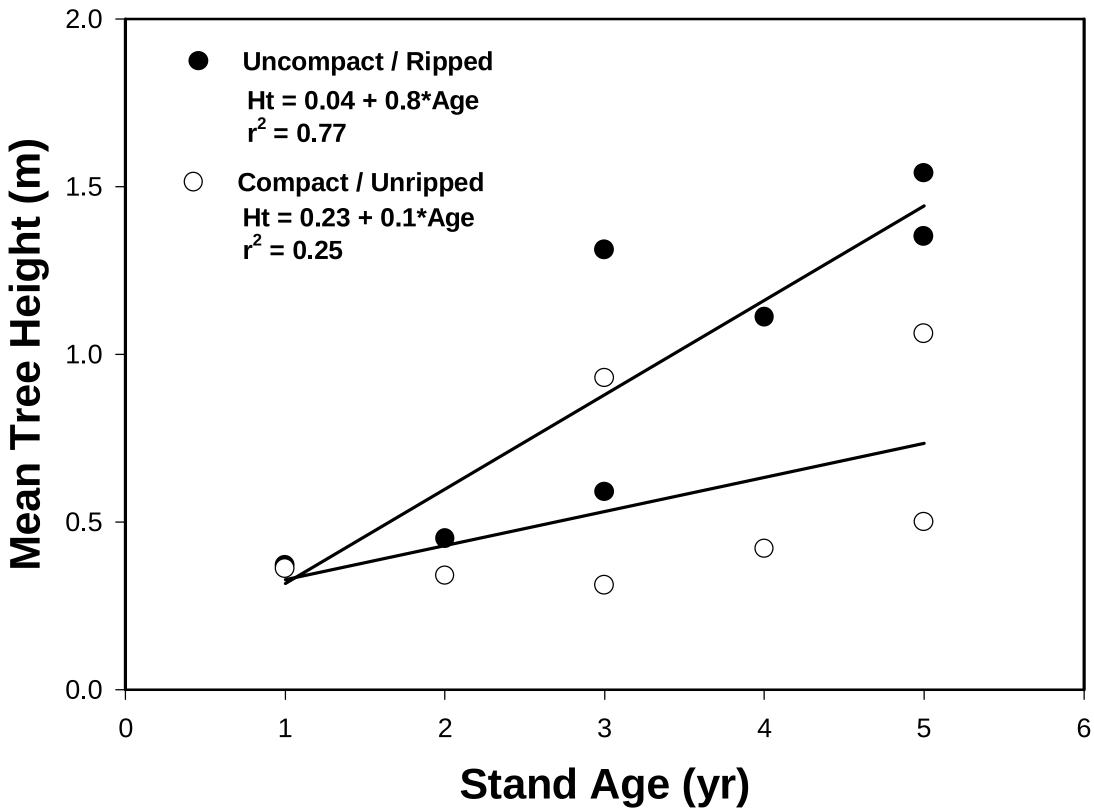

Fig. 2 Relationship between mine spoil compaction and tree height.

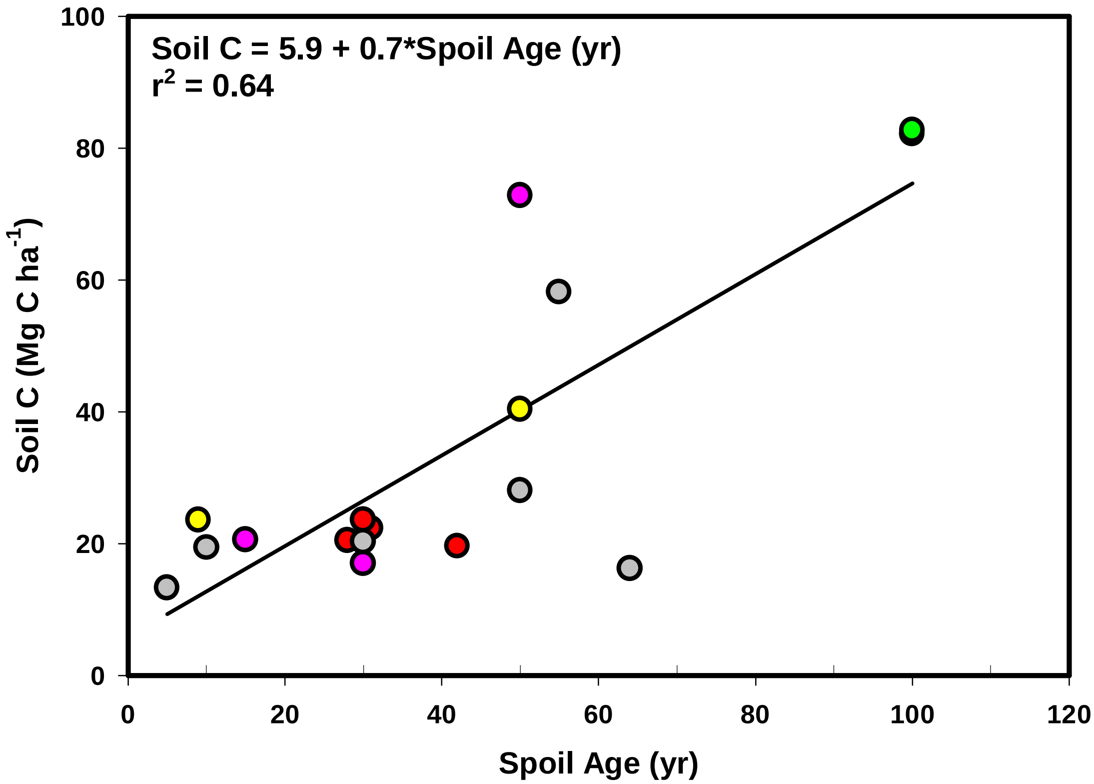

Fig. 3 Soil carbon content (0-50 cm depth) in mine spoils or increasing age at sites within the continental US and Canada.

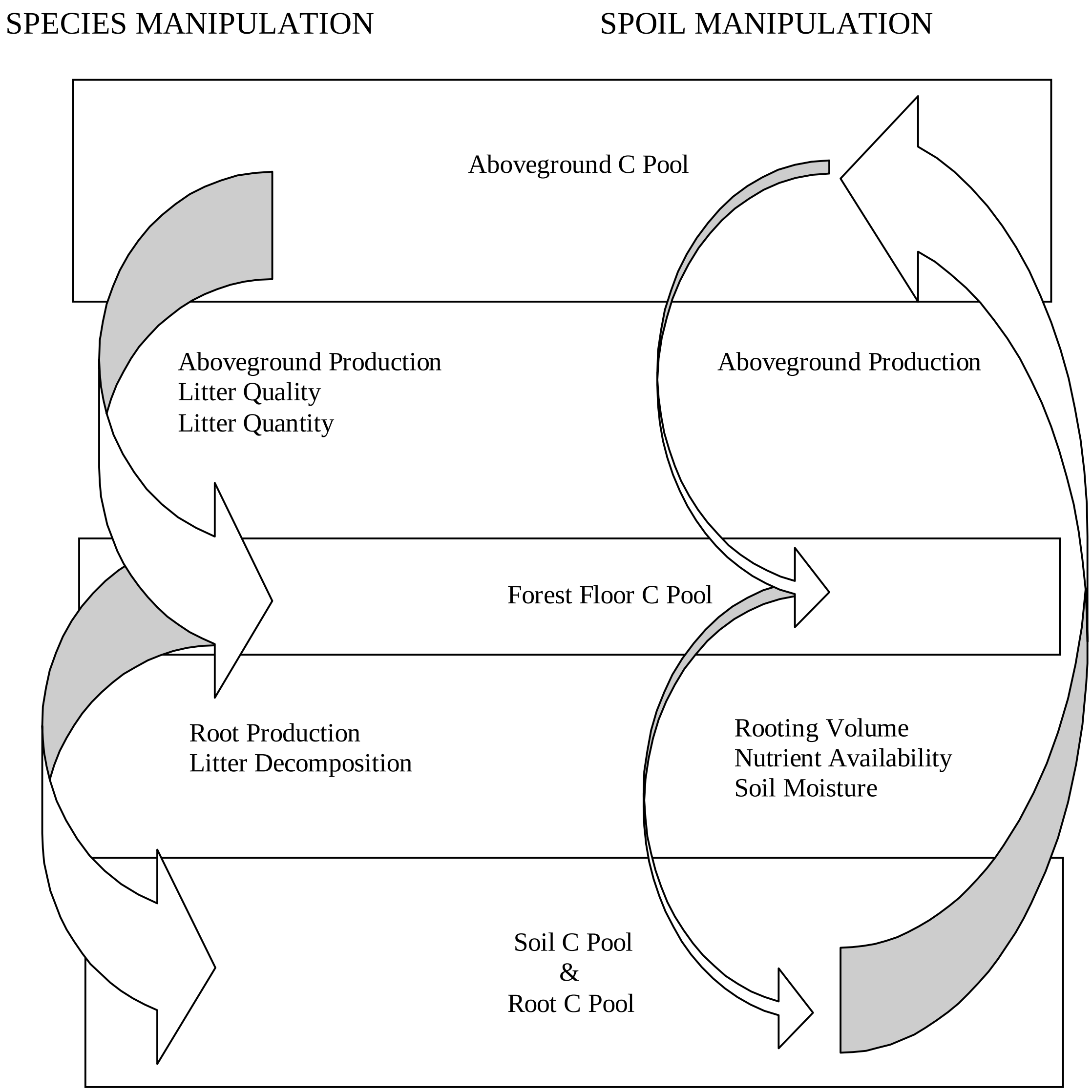

Fig. 4. Diagram illustrating the dominant effects of tree species and spoil manipulations on carbon cycling and storage. Species effect carbon pools via species-specific differences in aboveground production, litter quality and quantity, and rooting characteristics. Spoil type and depth influence both the production of biomass and the affinity for reclamation sites to store C in soil pools.

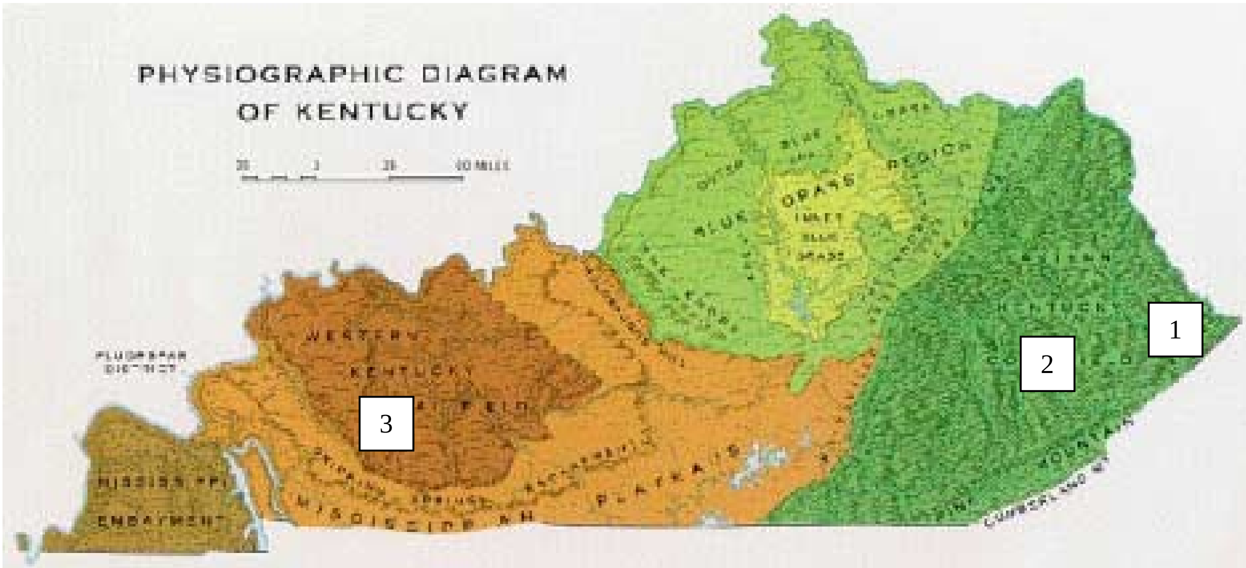

Fig. 5. Study locations within Kentucky's eastern and western coalfields regions.

WA W/L	YP WO/L	YP W/L	WP WO/L	YP WO/L	WP W/L
MIX WO/L	WP WO/L	MIX W/L	WA W/L	WA WO/L	MIX WO/L
WA WO/L	WA W/L	WP W/L	MIX WO/L	WP W/L	YP WO/L
YP W/L	MIX W/L	YP W/L	WA WO/L	MIX W/L	WP WO/L

Fig. 6. Tree species effects on carbon sequestration on mine lands study design (WA = white ash, YP = yellow poplar, WP = white pine, MIX = mixed species, W = with, WO = without, and L = black locust).

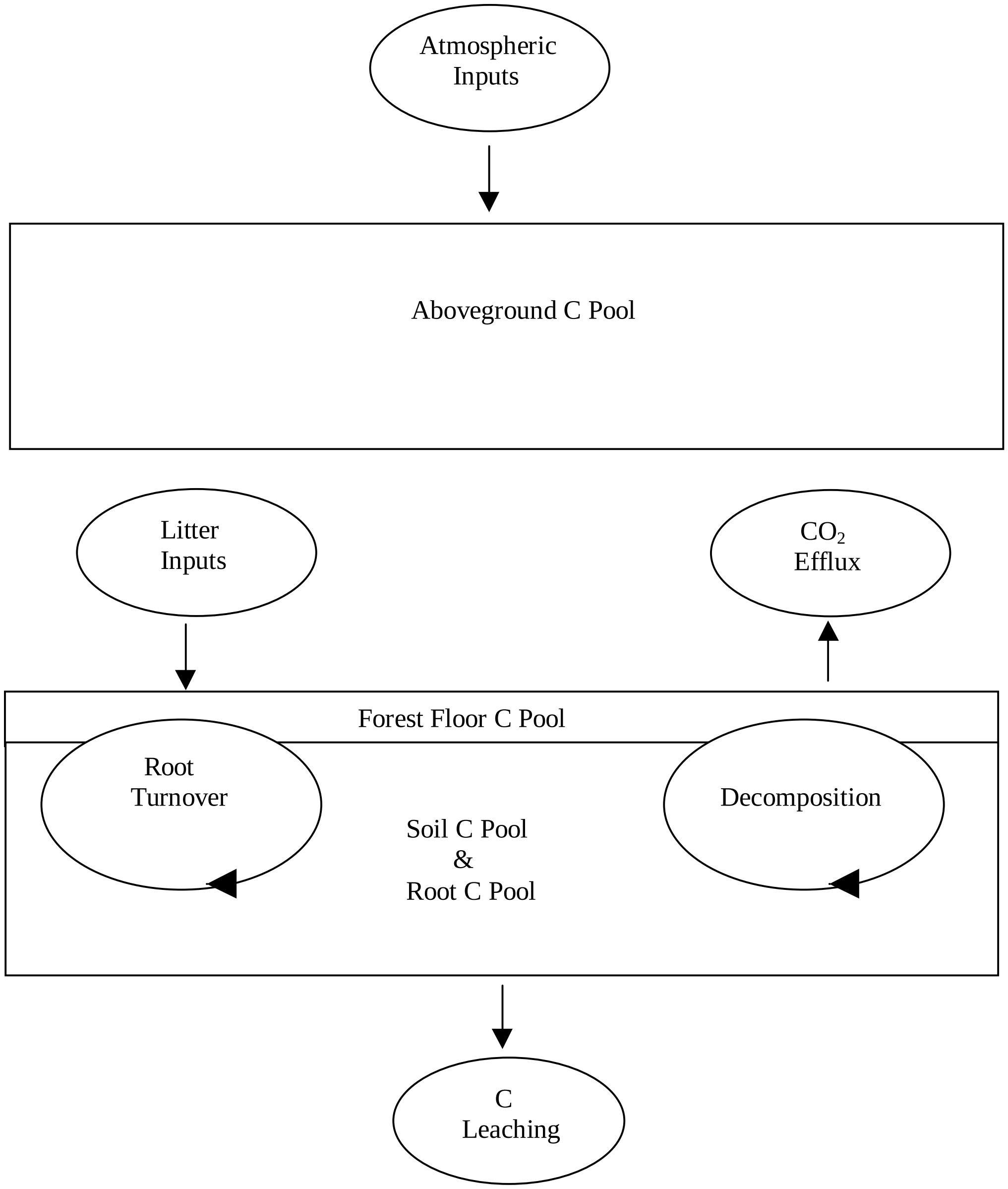

Fig. 7. Carbon pools, fluxes and processes to be measured in studies investigating species influence, spoil depth and spoil type effects on carbon sequestration on mine lands.