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Carbon Sequestration in Reclaimed Minesoils

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Minesoils are drastically influenced by anthropogenic activities. They are characterized by low soil organic matter (SOM) content, low fertility, and poor physicochemical and biological properties, limiting their quality, capability, and functions. Reclamation of these soils has potential for resequestering some of the C lost and mitigating CO_2 emissions. Soil organic carbon (SOC) sequestration rates in minesoils are high in the first 20 to 30 years after reclamation in the top 15 cm soil depth. In general, higher rates of SOC sequestration are observed for minesoils under pasture and grassland management than under forest land use. Observed rates of SOC sequestration are 0.3 to 1.85 Mg C ha^{-1} yr^{-1} for pastures and rangelands, and 0.2 to 1.64 Mg C ha^{-1} yr^{-1} for forest land use. Proper reclamation and postreclamation management may enhance SOC sequestration and add to the economic value of the mined sites. Management practices that may enhance SOC sequestration include increasing vegetative cover by deep-rooted perennial vegetation and afforestation, improving soil fertility, and

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alleviation of physical, chemical and biological limitations by fertilizers and soil amendments such as biosolids, manure, coal combustion by-products, and mulches. Soil and water conservation are important to SOC sequestration. The potential of SOC sequestration in minesoils of the US is estimated to be 1.28 Tg C yr^{-1}, compared to the emissions from coal combustion of 506 Tg C yr^{-1}.

I.   INTRODUCTION

Surface mining is the most common technique used for mining of coal and other minerals when they occur close to the surface. In the process, the surface is completely stripped of vegetation, and the earth and rock (overburden) overlaying the coal layer is removed from large continuous areas to provide access to the coal bed or mineral of interest. Surface mining, therefore, causes soil disturbance and degradation on a large land area, and generates a large volume of heterogeneous mass, consisting of freshly blasted overburden materials called "mine spoils," a term given to any unwanted earth material that is left unmanaged. Once the mine spoils are placed on reclaimed surfaces and utilized to support plant growth, either with or without topsoil, they are considered to be "minesoils" (Sencindiver and Ammons, 2000), mixtures of soil and spoil or overburden that are being managed. The properties of these mine spoils are directly controlled by the physical and geochemical properties of the rock strata from which they are derived.

Reclamation of minesoils is the process of returning the mined land to a useful (but not necessarily the original) state (Barnhisel and Hower, 1997; Bradshaw, 1997). The reclaimed minesoils are manmade or anthropic soils (Lal *et al.*, 2004). Reconstruction of an ecosystem and minesoil quality depends on vegetation for improving soil physical, chemical and biological conditions of disturbed sites (Bradshaw, 1987). Therefore, the recovery of minesoil quality and ecosystem function of disturbed site depends on reestablishment of vegetation that can thrive and sustain itself. The potential for sequestration of carbon (C) in reclaimed minesoils is high and merits serious consideration. Minesoils can be a significant sink for atmospheric carbon dioxide (CO_2) through formation of soil organic matter (SOM) and aboveground biomass accumulation. Akala and Lal (2000) showed that a reclaimed minesoil can sequester soil organic carbon (SOC) up to 30 Mg C ha^{-1} in 25 years.

The purpose of this paper is to collate, review, and synthesize available information worldwide on soil C sequestration in coal minesoils; describe physical, biological, and ecological processes; outline management practices which enhance C sequestration in minesoils; and identify research and development priorities for increasing the potentials for soil C sequestration in reclaimed coal minesoils.

II.   PROPERTIES OF MINESOILS

Minesoils are pedogenically young soils that are developing from mixtures of fragmented and pulverized rock material. Minesoils developing on surface-mined lands are characterized by having more rock fragments than the native soils, with rock fragment content ranging from 32 to 67 percent (Ashby *et al.*, 1984; Ciolkosz et al., 1985; Thurman and Sencindiver, 1986). An increase in coarse fragments is caused by incorporation of nonsoil materials into the minesoils. Physicochemical properties of these soils tend to inhibit soil-forming processes and plant growth. There is usually a lack of nutrients associated with SOM, including nitrogen (N) and phosphorus (P). Other problems include high acidity, absent or very shallow topsoil, absence of soil forming fine soil materials, and generally low fertility. Soil pH and associated properties impact nutrient availability and soil productivity, and influence revegetation in minesoils. Growth-limiting acidity in surface-mined soils originates from surface deposition of low-base-content overburden consisting primarily of sandstone or shale originating from low-base-content parent material, sulfur-bearing (pyrites, FeS_2) overburden layers, and waste coal (Mays *et al.*, 2000). Acidic conditions limit revegetation through plant toxicity by elements that become more available to plants at low pH and restriction of root growth into acidic spoils. Fertilization and liming to raise soil pH above 5.5 can improve conditions of the reclaimed minesoils for plant growth. Bradshaw (1983) recommended a minimum of 1000 kg ha^{-1} total N for proper plant growth and ecosystem development in reconstructed minesoils. The P availability may also be limiting due to high fixation capacities of exposed mine spoils (Bradshaw, 1983; Roberts *et al.*, 1988b).

Minesoil development over time may be the single most important edaphic factor determining the success of the reclamation plan. Surface environmental conditions typically lead to rapid weathering of the spoil in the early stages, but the rate of weathering decreases over time (Struthers, 1964). Rapid chemical reactions occur in spoil as the exposed material attains equilibrium with its new environment (Struthers, 1964). Freeze-thaw, shrink-swell, dissolution, leaching, oxidation, mechanical disruption by roots, SOM decomposition and incorporation, and aggregation of soil particles into peds are major pedogenic processes which differentiate minesoils properties and horizons (Roberts *et al.*, 1988a,b). Rapid changes in particle size distribution occur as spoil materials weather.

In many cases reclamation by heavy equipment results in compacted minesoils which exhibit reduction in porosity near the surface (Chong *et al.*, 1986; McSweetney and Jansen, 1984) and poor aeration. Compacted minesoils also lack notable soil structure (Indorante and Jansen, 1981; Fehrenbacher *et al.*, 1982; Thompson *et al.*, 1987), have higher bulk density values and lower infiltration rates than the original soils (Thurman and Sencindiver, 1986). The bulk density of productive natural soils generally ranges from 1.1 to 1.5 Mg m^{-3}, while minesoils often exhibit bulk density >1.6 Mg m^{-3} (Daniels and Zipper, 1997). Severely compacted minesoils (bulk density >1.7 Mg m^{-3}) with

less than 0.6 m of effective rooting depth cannot hold enough available water to sustain vigorous plant communities through protracted drought (Daniels and Zipper, 1997). A loose, non-compacted soil of 0.9 to 1.2 m depth is required to hold enough water to sustain plants through prolonged droughts (Daniels and Zipper, 1997). Soil compaction limits plant growth, as most species are unable to extend roots effectively through high bulk density minesoils. Soil compaction was the major soil factor limiting long-term revegetation success of older minesoils (5 to 20 years) in the Powell River Project watershed in southwest Virginia (Daniels and Amos, 1981). Lack of or poor soil structure also decreases hydraulic conductivity of minesoils (Shukla *et al*., 2004).

Extreme disturbance due to surface mining of coal causes drastic perturbations in the original soil profile, its properties and processes, leading to severe soil degradation. The sudden perturbation gives little time for soil's inherent resilience to respond. Severe loss of SOM leads to loss of soil quality and a decrease in soil capability and functions (Lal, 1997). Much of SOM losses can be attributed to lack of inputs from plant litter, loss of topsoil, mechanical mixing of A, B, and C horizons during removal and handling of overburden material, erosion, leaching and accelerated decomposition of SOM from the exposed topsoil. Similar to tillage, surface mining, in addition to mixing and stirring of soil, breaks up aggregates and expose organo-mineral surfaces otherwise inaccessible to decomposers.

The large and relatively rapid decline in SOC pool in minesoils indicates that there is a potential to enhance the rates of C sequestration in these soils with management practices that reverse the effects of degradation on SOC pools. The potential of SOC sequestration in minesoils depends on biomass productivity, root development in the subsoil and changes in minesoil properties resulting from overburden weathering (Haering *et al*., 1993). Temporal changes in SOC pools indicate improvements in soil quality as soils sequester C. Successful reclamation techniques with the potential for enhancing SOC sequestration are those that recreate minesoils that allow adequate growth and productivity of the reclamation species, which further improve minesoil properties through SOM accumulation.

III.   SOIL ORGANIC CARBON SEQUESTRATION

The SOC level in undisturbed soil is maintained through dynamic processes which reflect the long-term balance between additions and losses. Terrestrial ecosystems are generally large C sinks. Photosynthetic organisms reduce atmospheric C and store energy from solar radiation by the formation of complex C molecules. This bound energy is transferred to mineral soils in the form of litterfall, root turnover, and root exudates, and supports an intricate detrital trophic structure in the soil. Carbon represents nearly half of the mass of live biomass and detrital organic matter (OM) pools. Decomposition of OM completes the atmosphere–soil–atmosphere C cycle by emitting a portion of SOC to the atmosphere as CO_2, while a portion is incorporated

in the stable humus fraction in soil. Decomposition rates tend to be proportional to the amount of OM in the soil (Johnson, 1995). Therefore, over time and under relatively constant environmental conditions, rates of C additions and emissions tend to equilibrate and the amount of SOC stabilizes at a constant, near steady-state level. Mining and associated disturbances disrupt the SOC equilibrium relationship, causing severe losses of SOC, while reclamation and proper management practices lead to improvement of soil quality and restoration of SOC (Figure 1). Sequestration of SOC over time enables stabilization at a new near steady-state equilibrium which is determined by microclimate, physicochemical and biological properties of minesoils, land use, and the prevailing management practices. This new equilibrium may be similar, lower, or higher than pre-mining equilibrium (Figure 1). The residence time of C stored belowground can vary from <1 year to centuries (Parton *et al*., 1987; Buyanovsky *et al*., 1994).

The mechanisms responsible for stabilizing SOC may be categorized as 1) physical protection, 2) biochemical recalcitrance, and 3) chemical stabilization (Christensen, 1996). Chemical stabilization is the result of associations between decomposable organic compounds and soil mineral components (e.g., organic C sorbed to clay surfaces by polyvalent cation bridges or trapped between expanding layers of clays). Biochemical recalcitrance results from chemical characteristics of substrate itself (e.g., lignin and their derivatives or fungal melanins; Haider and Martin, 1981). The nature of various organomineral associations and their location and distribution within soil aggregates determine the extent of physical protection and chemical stabilization of SOC (Gjisman and Sanze, 1998). The same mechanisms also play major roles in stabilization and retention of SOC in minesoils.

IV.   SOIL STRUCTURE AND CARBON DYNAMICS IN MINESOILS

Accumulation of OM in minesoils improves physical properties by creating and stabilizing soil structure. Polysaccharides contribute to the formation of aggregates, while humic substances are involved in their stabilization. Soil structure plays a dominant role in the physical protection of SOM by controlling microbial access to substrates, microbial turnover processes, and food web interactions (van Veen and Kuikman, 1990). Relatively labile materials become physically protected from decomposition by incorporation into soil aggregates (Gregorich et al., 1991; Golchin *et al*., 1994) or by deposition into microbially inaccessible micropores. In addition to SOC sequestration, aggregation also improves physical, chemical, and biological properties of minesoils.

The stability of aggregates is controlled by the complex interaction between OM and mineral components. Soil management exerts a strong influence on the formation and stability of aggregates (Perfect *et al*., 1990; Tisdall, 1996; Angers *et al*., 1993). Complex organomineral compounds slow microbial degradation
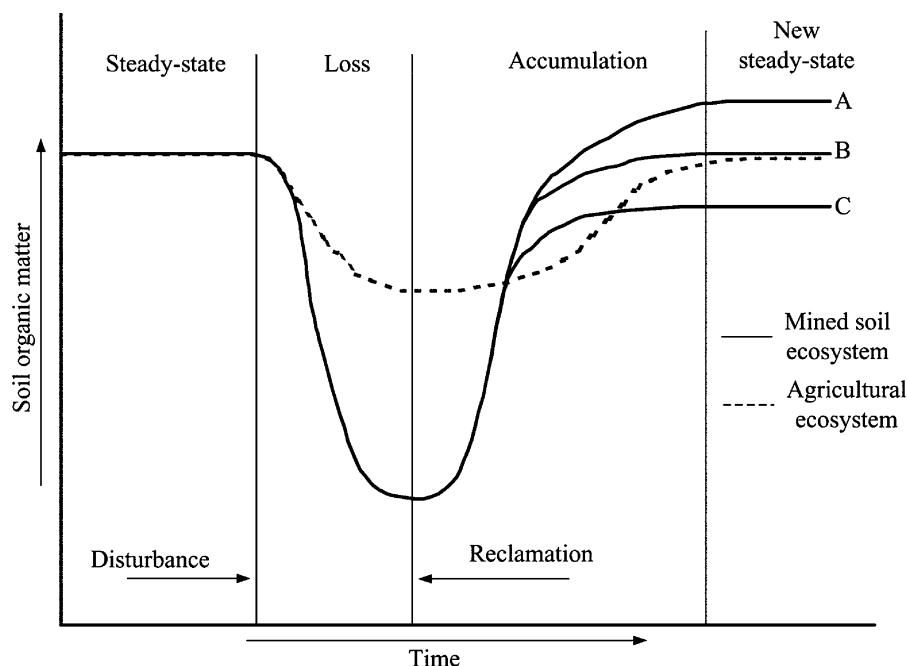
FIG. 1.   Conceptual model of SOC dynamics in mineland ecosystem (adopted with modifications from Johnson, 1995).

and contribute recalcitrant SOC that remains in soil for centuries. Soil OM stabilization may arise as a result of incorporation of polydisperse aliphatic or aromatic molecules, sorption of organic substrates onto clay minerals and sesquioxides (Ussiri and Johnson, 2004), or physical protection from decomposers (Christensen, 1996). The turnover of SOM is determined by biological, chemical and physical interactions and by environmental factors. Plant residues represent the main source of C required to maintain or increase SOM.

The rate and quality of C transfer belowground, and soil microbial activities are the main biological processes that control the dynamics of OM in minesoils. Plant residues returned to the soil are gradually altered through physical fragmentation, faunal/floral interactions, mineralization, and humification. Decomposition processes and OM turnover rates are influenced by management practices, climate, type and quality of OM, location of the OM within the soil, and physicochemical associations with mineral soil components (Batjes, 1999; Jastrow and Miller, 1997).

V.   CARBON ACCRETION IN MINESOILS

Mining and related activities cause drastic perturbation of terrestrial ecosystem, leading to severe soil degradation. There is severe loss of SOC due to enhanced mineralization, soil erosion, leaching (Lal *et al.*, 1998), reduced/lack of inputs of OM, mixing and compaction, which decrease physical protection against decomposition. Losses of SOC of as much as 80 percent of the original pool have been observed from scraped topsoils (Ghose, 2001; Akala and Lal, 2001). In a study assessing the shelf life

of minesoils in India, Ghose (2001) observed a 47 percent decrease in SOC in the first year, followed by gradual decrease until a steady-state level was achieved at 80 percent lower SOC than the initial concentration after 6 years. Akala and Lal (2001) estimated SOC pool losses due to surface mining to be more than 70 percent of the antecedent pre-mining concentration. The SOC content of reclaimed minesoils is typically very low compared to undisturbed soils. Therefore, the potential to increase the C capital of minesoils is significant.

Revegetation of minesoils is an important management option for mitigation of the negative impacts of mining and initiate ecosystem recovery. Soil restoration measures can reverse the degradation trends leading to positive changes in the ecosystem and SOC sequestration. Reclaimed soil can be used for different purposes including cropland, forest, grazing land, pasture and rangeland. Reclaimed minesoils develop recognizable horizonation relatively quickly and sequester C (Thomas and Jansen, 1985). A distinct A-horizon up to 15 cm thick can develop within 5 years after reclamation (Thomas and Jansen, 1985; Roberts *et al.*, 1988a,b; Akala and Lal, 2000). This horizon is distinguished from subsoil by the accumulation of SOM, loose soils due to root growth, and soil structure development (Akala and Lal, 2000). In a chronosequence study of minesoil reclamation in southwest Virginia, Daniels and Amos (1981) observed that an A-horizon up to 13 cm thick was formed in 5-year-old reclaimed minesoils. Thomas and Jansen (1985) investigated 8 coal mine spoils and observed that the most apparent change in all sites was the development of an A-horizon with darker color, high SOM content, and well-defined genetic soil structure. Akala and Lal (2000) examined a chronosequence of minesoils in eastern

Ohio and found that a distinct A-horizon with high SOM and well-defined genetic structure was formed within 5 years after reclamation.

The net rate of C gain following conversion of severely degraded land to productive agricultural or forestland have 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} have been used to predict the effects of reclaiming mineland in Europe and the United States (Nabuurs *et al.*, 2000; IPCC, 2000). In a survey of the available data on OM changes resulting from land conversion from cultivation to perennial vegetation or permanent grasslands, Post and Kwon (2000) reported rates of C accumulation ranging from −0.51 to 3.1 Mg ha^{-1} yr^{-1}, with an average accumulation of 0.34 Mg C ha^{-1} yr^{-1} in the top 30 cm for a variety of forest types ranging from tropical to temperate. The rates of accumulation in permanent grasslands were generally higher, ranging from −0.48 to 1.1 Mg ha^{-1} yr^{-1}, with an average of 0.74 Mg ha^{-1} yr^{-1} for the grassland biomes ranging from tropical dry lands to cool temperate steppe (Post and Kwon, 2000). Higher rates have been observed in minesoils (Table 1). In a chronosequence study to assess the SOC sink capacity of a reclaimed minesoil Akala and Lal (2001; 2002) reported that the top 0–30 cm of forest and grassland can sequester 37–45 Mg C ha^{-1} and 47–79 Mg C ha^{-1} over 21- and 25-year periods, respectively (Table 1). The rate of C accumulation was higher (2 to 3 Mg ha^{-1} yr^{-1}) in the initial period, and decreased to as low as 0.2 Mg ha^{-1} yr^{-1} 21 years after (Figure 2). The C sequestration rates were lower in subsoil than surface soil (Table 1). Maximum rates of 0.7 and 0.8 Mg C ha^{-1} yr^{-1} were achieved after 15 and 20 years for forest and pasture, respectively (Akala and Lal, 2002). Soils reclaimed with topsoil application reached equilibrium SOC level in the top 15 cm earlier than those reclaimed without topsoil application (Akala and Lal, 2002).

Forest lands differ from grasslands and croplands in that they can sequester a large amount of C for longer periods of time aboveground in trees and belowground in coarse roots. The live biomass C may be stored in trees for up to 100 years. The C in
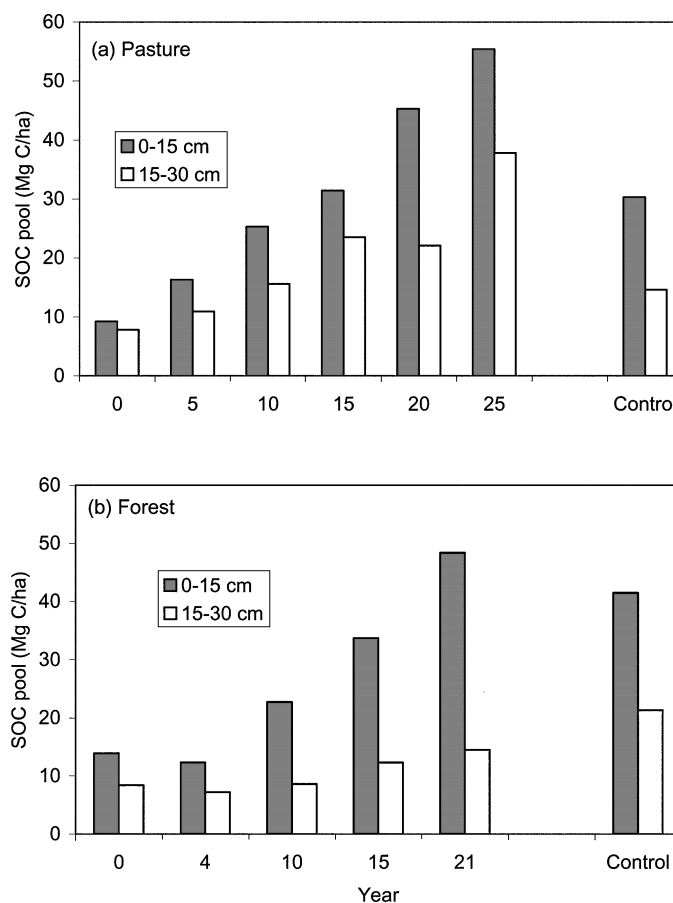

FIG. 2. Accumulation of SOC in the reclaimed minesoils under pasture and forest land use in southeastern Ohio. The control samples were collected from unmined 70-year-old pasture and 65-year-old forest (replotted from Akala and Lal, 2001).

the trees can also be harvested and stored as wood products such as paper, furniture, and in landfills for longer periods. Thus, C in forest lands, both in live tree biomass and in soils, has a longer residence time, making reclaimed minesoils converted to forest

TABLE 1

Carbon content and rate of C accumulation in mine soils following reclamation for various durations

Surface management	Years since reclamation	Soil sample depth (cm)	Gain in SOC content (Mg ha^{-1})	Rate of change (Mg ha^{-1}yr^{-1})	Reference
Pasture	0–25	0–15	46.2	1.85	Akala and Lal (2001)
	0–25	15–30	30.0	1.2	
	0–25	0–15	29.1	1.16	Akala and Lal (2002)
	0–25	15–30	7.7	0.3	
Pasture	5–25	0–10	14.8	0.75	Shukla et al. (2004)
Pasture + Pine	0–16	0–10	8.0	0.50	Bendfeldt et al. (2001)
Forest	0–21	0–15	34.5	1.64	Akala and Lal (2001)
	0–21	15–30	6.1	0.3	
	0–21	0–15	32.6	1.55	Akala and Lal (2002)
	0–21	15–30	4.5	0.2	

land a larger sink of CO_2. Most of the ecosystem C in forests is usually in soils; although SOC content varies depending on forest type, soil physical, chemical and biological properties, climate, topography, parent material and time (Morris and Paul, 2003). The long-term fate of sequestered C depends on the residence time of SOC pools, and consumption of the aboveground biomass. Forest harvest and biomass combustion returns C to the atmosphere. However, incorporation of wood biomass into wood products represents a significant reserve of terrestrial C (Nabuurs *et al.*, 2000).

The rate of C sequestration depends on productivity of the forest or grasses established on reclaimed sites and on minesoil quality. In temperate region, 40% of the C gained during 25-year forest plantation rotation remains stored within solid wood products (Winjum and Schroeder, 1997). On average, deciduous and pine temperate forest vegetation contain 131 and 160 Mg C ha^{-1} respectively, and about 130 Mg C ha^{-1} stored in SOM (Houghton, 1995). Vogt *et al.* (1995) reported that living biomass accounted for 40 to 62 percent of total ecosystem C, whereas SOM contained 33 to 50 percent of forest C. Richter *et al.* (1999) tracked the changes in C inventory over 40 years following conversion from row cropping to a loblolly pine (*Pinus taeda*) plantation in South Carolina. The pine ecosystem accumulated 180 Mg C ha^{-1} during the 40-year period. The annual accumulation was 4.3, 0.9, and 0.04 Mg C ha^{-1} yr^{-1} for tree, forest floor, and mineral soil (0–30 cm), respectively. Forest biomass accounted for 80 percent of added C inventory, while forest floor and mineral soil contributed 20 percent and <1 percent. In minesoil, an average SOC pool of 39 Mg ha^{-1} accumulated in the top 30 cm of soil for the first 21 years after reclamation at an average rate of 1.85 Mg ha^{-1} yr^{-1} (Table 2; Akala and Lal, 2001, 2002). However, the biomass accumulation in trees was not monitored in these studies. Young, aggrading forests are potentially strong C sinks. Temperate forest regions have a high potential as a sink of atmospheric CO_2. Based on the above- and belowground biomass measures in temperate forests, biomass increment is estimated at 4.1 Mg C ha^{-1} yr^{-1} (Winjum and Schroeder, 1997). With recommended management practices, tree biomass accumulation in reclaimed sites can be as high as in natural soils. Therefore, minesoils have great potential for C sequestration and mitigating CO_2 increase in the atmosphere.

The length of time that net SOC sequestration continues in minesoils after land reclamation is uncertain. The SOC increases rapidly over the first 20 years after minesoils reclamation (Bendfeldt *et al.*, 2001; Akala and Lal, 2001). The SOC accumulates at lower rates after 20 to 30 years. Model predictions based on 0 to 25-year chronosequence data indicated that it may take 100 to 150 years for the SOC pool to attain steady-state equilibrium in reclaimed minesoils (Akala and Lal, 2001; 2002).

The accumulation of C stocks, long-term minesoil quality, and ecosystem restoration in mined sites depends on the ability of reclaimed minesoils to support establishment of vegetation that can thrive and sustain itself. Reconstruction of an ecosystem and minesoils quality depends on vegetation for improving soil physical, chemical and biological quality of disturbed site. Successful revegetation and subsequent C sequestration in minesoils requires judicious management of physical, chemical and biological parameters of soils and vegetation. The important vegetation parameters to consider include species selection, seedbed preparation, time of seeding and seed rates, fertilizers and soil amendments, application of mulch to assure vegetation establishment (Barnhisel and Hower, 1997; Andrews *et al.*, 1998). Low SOM content, infertility, micronutrient imbalances or toxicity, low N and P availability, soil/spoil compaction during grading operations, shallow soil depths, low moisture holding capacity, high electrical conductivity, and extreme pH result in unfavorable conditions that can affect SOC sequestration in minesoils. Evidence from a number of North American sites demonstrates that under adequate soil conditions and proper management, forest biomass production in reclaimed minesoils can meet and even exceed that of natural unmined soils (Torbert and Burger, 2000). White pine (*Pinus strobus*) height ranged from 0.9 to 6.9 m after 10 years' growth across 34 reclaimed mine sites in southwestern Virginia (Torbert *et al.*, 1988). Burger and Zipper (2002) projected similar height growth for white pine grown on average quality minesoils and unmined sites in 25-year-old stands, while on deeper, high–quality minesoils white pines may attain a height of 21 m at 25 years and 30 m after 50 years. Wade *et al.* (1985) observed similar growth rates in natural soils and reclaimed minesoils in eastern Kentucky for pine and hardwood species. In Virginia, Torbert *et al.* (1988) reported some white pines of 50-year base age on minesoils with higher yield than natural soils. Trees with shallow rooting depth had slower growth rates than those with deep root systems. Major factors that affect tree species establishment and growth rate in reclaimed minesoils are: 1) soil depth, 2) soil toxicity, 3) soil compaction, and 4) weed competition (Torbert and Burger, 2000).

Rooting depth is an important minesoil property controlling tree productivity and C sequestration. Physical limitations to forest growth on minesoils 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 root penetration, and altering drainage of water and water holding capacity within the rooting zone (Bell *et al.*, 1994), thereby reducing the effective rooting depth. Andrews *et al.* (1992) examined 78 reclaimed mine sites planted with white pines across a three-state region. Rooting depth was the most important factor affecting tree height in minesoils. Poorest growth occurred on shallow minesoils and in areas where compaction was the most severe. Other important management factors and processes which influence the rate of change in SOC contents in aggrading terrestrial ecosystems include 1) increasing the input rates of OM, 2) changing the decomposability of OM inputs that increases litter and light fraction OM, 3) incorporating OM deeper in the soil, either directly by enhancing belowground inputs or indirectly by surface–mixing soil

organisms (e.g., earthworms), and 4) enhancing physical protection through intra-aggregate or organomineral complexes (Post and Kwon, 2000). These conditions are generally enhanced by permanent perennial vegetation.

VI. MANAGEMENT OF MINESOILS FOR CARBON SEQUESTRATION

Conceptually, increased C sequestration can be achieved by enhancing the natural biological processes that assimilate CO_2, such as increased productivity of lands, and then allocating the assimilated C to long-lived plant tissues and/or pools of SOM resistant to microbial decomposition. Surface mining often results in soil productivity limitations for revegetation not encountered in other land-use situations. Degraded minesoils are often compacted, and characterized by acidic pH, low levels of principal nutrients, poor soil structure and limited moisture-retention capacity (Haering et al., 2000). Management of minesoils for C sequestration requires establishing and maintaining the vegetation cover, and achieving high biomass accumulation in the reclaimed sites. These conditions can be achieved by afforestation or establishment of other perennial vegetation. In addition to its role in erosion control, vegetation encourages minesoil development and contributes to productive post mining land use. A minesoil pH range of 6.0 to 7.5 is ideal for vegetation and forages. When pH falls below about 5.5, reduced growth for some species occurs due to metal toxicities (Al, Fe, Mn), P deficiency due to fixation, and reduced population of N fixing bacteria. However, some tree (e.g., *Pinus* spp.) and native plant species can grow well in soils with pH 4.0 to 5.5 (Daniels and Zipper, 1997). Too high pH may also inhibit growth due to micronutrient (Mn, Zn, Fe) and P deficiency through fixation by carbonates, though this is rarely a problem in minesoils. Liming can correct low pH and ameliorate metal toxicities associated with high acidity. Newly reclaimed minesoils often require fertilizer application (N, P, K, Ca, and Mg) for the establishment and maintenance of vegetation. Mine spoils are essentially devoid of N initially. The N required to sustain plant growth over time can come initially from fertilization and subsequently from symbiotic microbial N-fixing legumes. Reclamation of minesoils with organic amendments enhances soil fertility, improves soil structure and moisture characteristics and enhances C sequestration.

Reclaimed minesoils have a high potential to sequester C through biomass production and accumulation of SOC in minesoils. Land management options designed to increase terrestrial C inventories include improving both present land-use practices as well as land-use conversion (Lal et al., 1997). Improved management practices for C sequestration in minesoils include: techniques to minimize soil compaction, mulching to minimize erosion and improve soil moisture, manuring and use of other biosolids and fertilizers to improve soil fertility, applying SOM to improve physical properties of minesoils, introducing N fixing plants for long-term fertility improvement, and conserving and recycling water. Success in the reclamation of surface mine sites

depends on the rapid formation of a surface horizon containing high SOM content (Tate et al., 1987). The low SOM content of stored topsoils, coupled with compaction by heavy equipment during land grading, causes unfavorable conditions for root development and SOC enhancement in subsoil (Thompson et al., 1987) and influences the C sequestration. Strategies for improving C storage in productive forest include fertilization, thinning, and prolonging the rotation cycle (Nabuurs et al., 2000).

The quantity and quality of SOC affect and are affected by plant production. The SOC storage in soils is controlled by the balance between input from plant, animals, and microbial residues and other biosolids and output through decomposition, erosion, and leaching. The rate of SOC sequestration in minesoils depends on biomass productivity, root development in subsoil, OM decomposition and its stabilization by soil aggregation, adsorption, and humification. Roots and litter are the major contributors to SOC pools. Improvement in soil aggregation is an important factor influencing minesoil development (Boerner et al., 1998; Malik and Scullion, 1998) and SOC sequestration. Changes in minesoil properties significantly impact biomass productivity and pedogenic processes that lead to SOC sequestration in minesoils. The SOC sequestration in minesoils depends on soil organisms and on the processes moderated by the interactions of these organisms and their environment (Figure 3). Sequestration of SOC in soils is the result of incomplete decomposition; long-term SOC storage is achieved through alterations of OM through processes such as humification and OM translocation downward in the soil profile. The amount of SOC in minesoils tends to reach a steady-state equilibrium dictated by soil physical and chemical properties, plant management and microbial community structure (Figure 3; Morris and Paul, 2003).

While the rates of SOC sequestration in minesoils are high and promising from the standpoint of mitigating CO_2 emitted to the atmosphere when coal is burned, there is still uncertainty regarding the dynamics of SOC sequestration and best land-management strategies to ensure the permanence of sequestered C. Also, it is reasonable to assume that if knowledge gained from studies of reclaimed lands were combined with that from agricultural and forest ecosystems, then the likelihood of successfully mitigating gaseous CO_2 emissions by way of SOC sequestration would be enhanced.

VII. THE ROLE OF SOIL AMENDMENTS IN SOIL ORGANIC CARBON SEQUESTRATION

Despite physical, chemical, and biological plant limitations encountered in reclaimed lands, minesoils have large C sequestration potential. Surface-mined sites lack the OM necessary for optimum soil functioning, so the addition of organic amendments initiates nutrient cycling, helps overcoming other chemical and physical limitations, and provides a receptive environment for vegetation. Organic amendments address these adverse conditions through variety of mechanisms, including direct or indirect contribution to releasing nutrients, stabilization of toxic
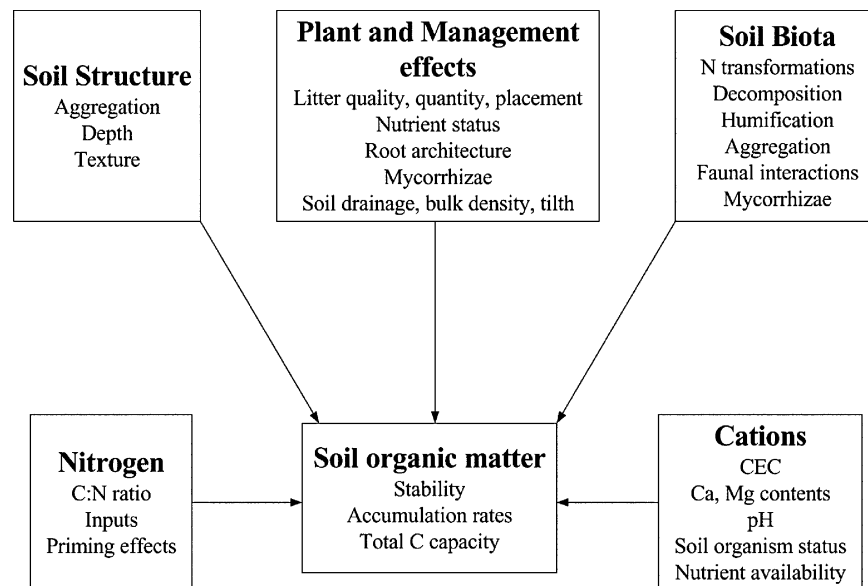
FIG. 3. Biological and chemical factors influencing SOC sequestration in minesoils (modified from Morris and Paul, 2003).

metals, improving soil structure and moisture characteristics of minesoils, and by directly increasing the SOM pool. Organic materials in different forms commonly used to restore and rejuvenate degraded minesoils are presented in Table 2. Amending minesoils with addition of organic materials increases the success of reclamation efforts. Organic materials such as animal manure, sewage sludge, or compost promote soil ecosystem recovery and encourage the development of self-sustaining plant and microbial communities. Organic materials can be used either as amendments which are incorporated into the surface or subsurface of disturbed soils or as mulches which are surface modifiers. Most organic amendments contain varying contents of undegraded OM (such as wood chips, plant residues, tree bark in compost) and humus, which plays an important role in the reclamation process by stimulating biological activity and releasing nutrients for plants.

A.   Biosolids

Biosolids, or sewage sludge, are the end products of wastewater treatment, which can be in a number of forms, including liquid, sludge cake, dewatered and dried, heat-dried, alkaline treated or composted (Walker, 1994). Biosolid products may be stabilized by lime or alkali, aerobically or anaerobically, composting, or heating to reduce pathogen level. The use of the resulting biosolid products and their impacts on minesoil vary considerably depending on the method of stabilization. Amending minesoils with biosolids increases SOC, CEC, soil nutrient levels and promotes soil ecosystem recovery after mining. Added OM increases aggregate stability and moisture holding capacity and decreases soil bulk density. Roberts $et\,al.$ (1988b) concluded that mine spoils treated with biosolids at $\geq 56\,\mathrm{Mg\,ha^{-1}}$ sustained higher forage yield than minesoils amended with lime and fertilized native topsoil. Bendfeldt $et\,al.$ (2001) observed a decrease

in bulk density on minesoils treated with biosolids 16 years after reclamation. Pichtel $et\,al.$ (1994) determined that biosolids applied at a rate of $224\,\mathrm{Mg\,ha^{-1}}$ were equivalent to limed and fertilized topsoil as a reclamation amendment for a very acidic mine spoil. Biosolids are often an excellent amendment for mined soils where the original topsoil contains low OM, or where topsoil substitutes such as overburden material or subsoil are used. Minesoils amended with biosolids at the Powell River Project in southwest Virginia produced higher forage quality and more persistent stands than minesoils reclaimed with fertilizers (Daniels and Haering, 1994). In prime farmland reclamation, deep ripping of subsoil combined with addition of biosolids at $22\text{--}44\,\mathrm{Mg}$ $\mathrm{ha^{-1}}$ increased corn ($Zea\,mays$) and sorghum ($Sorghum\,biedon$) yields. Yields from deep ripped and biosolids amended plots exceeded control (undisturbed farmland) 1 year after soil reconstruction (Powell $et\,al.$, 1986). Zhai and Barnhisel (1996) observed increased corn yield when biosolids were applied to the subsoil at a rate of $34\,\mathrm{Mg\,ha^{-1}}$ and incorporated with chisel plow before topsoil replacement. Manuring has the same advantages as biosolids; however manures have higher N contents than biosolids (Table 2) and pose no risks of high levels of micronutrients and heavy metals (i.e. Cd, Cr, Ni, Pb, and B) found in some biosolids. Manures have not been used extensively in reclamation because of the high moisture content and transportation costs involved in moving the bulk volume from their source to the mine sites. Transport expenses for biosolids are usually paid by the originating municipality.

B.   Mulching

Mulches are organic or inorganic materials applied on or near the surface of soil as a temporary surface cover and soil conditioners for stabilizing the surface and improving microclimatic conditions for the establishing vegetation. Crop residues

TABLE 2
Organic amendments for reclamation of minesoils

Materials	Types/forms	Role in minesoils
Plant residues	Straw, wood chips, sawdust	Mulch Increase SOM Stimulate biological activity Improve soil physical properties Nutrient source
Compost	Variable	Stimulate biological activity Nutrients source Improve physical properties Increase SOM
Manure	Poultry, cattle, swine	Improve soil fertility Increase soil organic matter Stimulate biological activity Improve physical properties
Biosolids	Anaerobic/aerobic digested, Lime stabilized, papermill sludge, municipal solid waste	Increases soil organic matter Increase CEC Stimulate biological activity Improve soil physical properties Increase or decrease pH Improve nutrients Can have negative environmental impact
Fly ash	Coal combustion by-product	Increases soil porosity Liming effect Source of micronutrients Improves soil physical properties Can have negative environmental impact
FGD	Coal combustion by-product	Liming effect Source of cations Improves soil aggregation

TABLE 3
The world coal consumption (million tons)

Region/country	Historical 1990	Historical 2000	Projection 2010	Projection 2025	Annual % change
North America	971	1168	1325	1680	1.6
USA	903	1084	1229	1567	1.6
Western Europe	894	559	513	463	−0.9
United Kingdom	119	64	65	49	−1.5
Germany	528	264	258	232	−0.5
Eastern Europe	1376	811	788	724	−0.6
Russia	497	267	298	297	0.2
Other former Soviet Republics	352	154	143	138	−0.7
Asia	1821	2262	2889	4238	2.6
China	1124	1282	1740	2757	2.9
India	242	359	430	611	2.2
Japan	125	160	178	202	0.8
Middle East	66	94	116	142	1.7
Australia & New Zealand	106	143	158	201	1.3
Africa	152	187	206	268	1.4
World Total	5307	5115	5881	7574	1.5

Source: Energy Information Administration (EIA), 2004.

or humus, 4) reducing soil surface temperature extremes, 5) increasing structural stability and permeability of minesoils, 6) decreasing surface crust formation, 7) reducing weed germination and growth, and improving microclimatic conditions for the desired species, and 8) serving as substrate for beneficial soil organisms (Norland, 2000). Organic mulches are preferred in minesoils because they provide needed microflora and fauna, OM and nutrients to heterogeneous disturbed soil that is usually low in microbial activities (Slick and Curtis, 1985).

C. Liming

Low pH inhibits natural revegetation of reclaimed minesoils (Skousen *et al.*, 1994). Soil pH range of 6 to 7.5 is ideal for forages, shrubs, and deciduous trees (Daniels and Zipper, 1997). Soil pH below 5.5 usually reduces legume and forage growth due to metal toxicities (i.e., Al, Fe, and Mn), P fixation, and reduced population of N fixing bacteria (Daniel and Zipper, 1997). However, some tree species such as pines (*Pinus* spp.), and some native plants grow satisfactorily at lower pH (4.0 − 5.5). Strongly acid spoils (pH 3.5–5.5) results in unusually low corn (*Zea mays*) and soybean (*Glycine max*) yields (Dancer and Jansen, 1987). Too high soil pH may also inhibit plant growth due to pH induced micronutrients deficiency.

The total acidity of a soil is the sum of active and residual (potential) acidic concentration in the soil. Active acidity is the concentration of H^+ in the solution, while the nondissociated

from agriculture, commonly straw and hay, are often used as mulch. Straw mulches are composed primarily of stems of cereals such as wheat (*Triticum aestivum* L) or oat (*Avena sativa* L), and are commonly applied at rates of 2–5 Mg ha^{-1} after the disturbed site has been fertilized and seeded (Noorland, 2000). The rates are typically adjusted based on slope, erosion potential and other site-specific characteristics. The major roles of mulches in reclaimed minesoils include: 1) preventing loss of water by increasing infiltration, increasing the total and available moisture holding capacity of the soil and increasing surface wetness, 2) increasing soil stabilization by reducing surface erosion by wind, water and raindrop impact, 3) increasing soil OM

acid is considered potential acidity. In minesoils, contributors to residual acidity include S, Al, Mn, and Fe, while H contributes to active acidity. For adequate liming of an acidic minesoil/spoil, both active and residual acidity must be neutralized (Mays *et al.*, 2000). The lime requirement of a minesoil/spoil material is related not only to its pH, but also to S, Al, Mn and Fe content. Their concentration and activity of play major role in buffering capacity and cation exchange capacity (CEC) in minesoils. Liming neutralizes growth-limiting acidity in mine spoils by contributing Ca^{2+} and other basic cations, which increase the pH of the acidic soils. Liming improves the degraded land by increasing soil quality and productivity.

D.   Coal Combustion By-Products

Restoration of severely degraded soils with fossil-fuel combustion by-products and other waste materials achieves ecological, environmental and societal benefits, and also enhances C sequestration by enhancing minesoils productivity. Two major coal combustion by-products with potential for use in minesoil reclamation to promote C sequestration are fly ash and flue-gas desulfurization (FGD) product. Fly ash is a coal combustion residue with an aluminosilicate composition comparable to that of a soil, with small contents of quartz, mullite, hermatite, magnetite, and variable amounts of unburnt C (Qafoku *et al.*, 1999). Fly ash contains considerable quantities of Ca, K and Na, and low quantities of P, B, and trace elements, including Cu, Zn, Mn, Mo, Ni, and Se, but no C and N (Carlson and Adriano, 1993). The FGD by-products are produced by newer SO_2 scrubbing technologies such as pressurized fluidized bed combustion (PFBC) and lime injection multistage burners (LIMB), and are mainly composed of alkaline materials consisting of calcite or dolomitic limestone (CaO, $Ca(OH)_2$, and MgO), sulfur-bearing compounds ($CaSO_4$, $CaSO_3$, $MgSO_4$), and fly ash (Crews and Dick, 1998). Fly ash is mainly used to modify texture in soils and as a source of trace nutrients for plants, while FDG by-products are mainly used for liming, as a source of divalent cations, and aggregation improvement. Coal combustion by-products contribute Ca^{2+} and other basic cations which increase pH in acidic minesoils and improve soil structure. Sale *et al.* (1997) observed decreases in bulk density and the modulus of rupture and increases in aggregation in soils amended with fly ash. In addition, fly ash increases porosity, water-holding capacity, pH, conductivity, and dissolved SO_4^{2-}, CO_3^{2-}, Cl^-, and basic cations (Matsi and Keramidas, 1999). Fly ash improves yield from minesoils for number of crops including cucumber (*Cucumis sativus*) and corn (Jiang *et al.*, 1999), barley (*Hordeum vulgare*; Sale *et al.*, 1996), and wheat (*Titicum aestivum*; Triphany and Sahu, 1997). The addition of low-B fly ash at 50 g kg^{-1} of soil increased rye grass (*Lollium perenne* L.) biomass up to 80% over non-treated Mediterranean acid soils (Matsi and Keramidas, 1999). The increase was attributed to increase in soil pH because of the liming effect of fly ash.

The potential of using coal combustion by-products to enhance C sequestration in minesoils is generally high when by-products are combined with organic amendments, such as mulch from agricultural residues, and biosolids such as sewage sludge or manure (Haering *et al.*, 2000). The organic amendments can have beneficial effects that can extend those of the combustion by-products. Potential benefits include improving soil structure, moisture retention capacity, and soil fertility. Inorganic and organic soil amendments both contribute to soil tilth but do so by different mechanisms that act in a complementary way. The Ca^{2+} and other divalent cations from fly ash promote flocculation between soil particles and stabilize soil structure through cation bridging, while organic matter adsorbs to the minerals soils and form a more reactive network for water and nutrients interactions in the soil (Palumbo *et al.*, 2004). The interaction of OM with soils is enhanced by Ca^{2+}, thus the addition of both organic and inorganic amendments would provide synergistic benefits to soil improvement. For example, OM binds essential cation/nutrients by acting as ion buffer to make micronutrients available for plant uptake. It can also stabilize toxic metals by immobilizing them in soil thereby reducing their pollution effects and toxicity to plants. The FGD by-product application is effective in correcting acidity with or without organic additions. However, application with sludge or compost decreases the potential for metal toxicity (Hao and Dick, 2000).

The potential for additions of soil amendments containing energy related by-products to improve degraded minesoils and beneficially utilize energy by-products is large. However, there are critical knowledge gaps on the appropriate combination of materials to be added, application techniques, site conditions and required management. In addition, the optimal strategy for rapid enhancement of C sequestration is not currently known.

VIII.   ROLE OF ROOTS IN CARBON SEQUESTRATION

Roots provide a path for movement of C and energy to deeper mineral horizons. Therefore, root production and turnover have a direct impact on the biogeochemical cycle of C in terrestrial ecosystems. Understanding belowground processes is essential to relating these with aboveground processes. The transfer of C belowground by roots may be a major input to SOC, but is quantitatively the least understood, due to the technical difficulties associated with its measurement (Izaurralde *et al.*, 2001). Roots contribute to SOC as organic debris left in soil when a plant dies or through exudation of organic substances during plant growth. These exudates, called rhizodeposits, consist of soluble compounds, secretions, and lysalates and dead fine roots. The contribution of root C is controlled by root productivity, turnover rates, exudation, mycorrhizal colonization, and soil characteristics, and these factors vary with vegetation. The fine root contributions to SOC range from 33 to 67 percent of the annual NPP in forest ecosystems (Grier *et al.*, 1981; Santantonio and Grace, 1987). Balesdent and Balabane (1996) used a $\delta\,^{13}C$ technique to calculate the contribution of corn roots to SOC storage in some soils in France. They found that corn roots incorporated 57 g C m^{-2} $year^{-1}$; this rate was 58 percent more than combined incorporation by leaves and stalks. These results suggested a

high belowground production and slow biodegradation of root-derived organic C. Swinnen *et al.* (1995) used ^{14}C pulse labeling to study rhizodeposition of winter wheat and spring barley. They found that total rhizodeposition accounted for 450 to 990 kg C ha^{-1} yr^{-1}, about 7 to 15 percent of net plant assimilation and twice as much as the mass of roots left after harvest. Therefore, deep-rooted plant species have the potential of increasing SOC sequestration by transferring more OM into deeper horizons.

IX. MONITORING SOIL CARBON SEQUESTRATION

In natural soil systems, organic C varies in space and time. Spatial variability is linked to well known drivers (e.g., parent material, climate, topography) operating over hundreds to thousands of years. In minesoils, this natural spatial distribution is lost due to the drastic landscape disturbance associated with mining and reclamation operations. Thus, minesoil properties may exhibit spatial trends that are a function of mining and soil reclamation processes, and the samples may not be spatially independent. Sampling techniques appropriate to natural soil systems that assume independence of the samples may not be adequate in reclaimed minesoils. Berg (1978) discussed this sampling issue and concluded that there are no general guidelines regarding the sampling of drastically disturbed lands. He suggested that where variability is known, meaningful sampling guidelines could be established. Schafer *et al.* (1980) noted that across a distance of 1 to 100 m, physicochemical properties of minesoils varied more compared to undisturbed soils, while across 100 to 1000 m, variability was lower in minesoils than in undisturbed soils. These differences in variability over different scales were attributed to overburden and topsoil handling procedures which result into a backfill which is mixed, giving more homogenous physicochemical properties across the larger landscape (Schafer *et al.*, 1980).

The aim of sampling is to reveal information about a complex population so that meaningful statements can be made with a given degree of confidence. The variation (i.e., variance) is the key statistic that determines the number of samples needed across the landscape. Ideally, sufficient samples must be collected to account for all the variations across the landscape. If the variation across the landscape is large, then many samples are required, given the level of error that can be tolerated. Geostatistical methods can be used to determine optimum sampling strategies on reclaimed minesoils (Dollhopf, 2000). Application of geostatistical methods in regional soil survey revealed three- to ninefold gain in sampling efficiency compared to estimates obtained by conventional statistics (McBratney and Webster, 1983). In reclaimed minesoils, applications of geostatistical methods have shown less sampling than that determined by conventional statistics (Dollhopf and Bearden, 1994; Hardy *et al.*, 1991). Geostatistical approaches allow sampling while taking into account spatial variability and sample dependence across a landscape (Dollhopf, 2000).

Direct methods for detecting changes in SOC in time and space are based on field sampling and laboratory determinations. The concentration of C (g kg^{-1}) in native soil can be determined with high accuracy by the dry combustion methods on dry, sieved and homogenous samples. In reclaimed minesoils, C occurs both in inorganic (carbonates and bicarbonates) and organic forms. The organic C pool is a mixture of coal particles dispersed during mining and reclamation operations and C resulting from incorporated plant detritus. Presence of fossil C contamination creates additional uncertainty in measured pools and rates of SOC sequestration in reclaimed minesoils. Reported rates of C sequestration are generally much higher than typically measured in cropland and rangeland soils, raising questions about their accuracy, since in some studies the contribution from coal particles are not accounted for. Lack of standardized sampling protocols in assessing C pools in reclaimed minesoils, given the variability of soil properties at these sites, and lack of standard methods of measurement to account for fossil C creates uncertainty concerning the SOC pool sequestration rates.

Depending on mining and reclamation techniques, the amount of fossil C (old C) can be substantial. Rumpel and Kögel-Knabner (2001) reported that lignite-C accounted for 13 to 96 percent of the total organic C in soil samples from forests established on lignite-rich overburden without topsoil application. Because of their high C content and light weight (>50% C by weight and >70% C by volume; Crowell, 2000), coal particles, even in small amounts, can introduce serious errors in SOC measurement. Against the large C background represented by coal particles, it is difficult to detect small increments of recently-deposited or plant-derived SOC.

Coal evolves from decomposition of organic debris in swamps and anoxic environments. During the decomposition process, less complex molecules such as proteins and carbohydrates are lost, while the aromatic moieties accumulate, leading to formation of peat, and then coal of various ranks (Crowell, 2000). The difference in structural composition is utilized in spectroscopic techniques to estimate the quantity of coal in minesoils. Spectroscopic methods (e.g., NMR analysis) detect differences in structural composition. While fresh plant material is mainly composed of carbohydrates, proteins, lignin and lipids, coal is dominated by aliphatic and aromatic structures which are formed during coalification. This highly aromatic macromolecular structure contributes to the refractory characteristics of coal. The relative abundance of the specific functional groups can be used to estimate the quantity of coal in soils (e.g., aryl group content; Skjemstad *et al.*, 2002). Radiocarbon dating is also used to quantify coal in soils. This method works based on the principle that coal is composed of C which was deposited several million years ago and consists only of stable C isotopes. Therefore, radiocarbon measurements can be used to quantify the coal contribution to the organic matter mixture of coal-rich minesoils (Rumpel *et al.*, 2000). Chemical methods involve treating samples with chemicals which remove/destroy organic matter, leaving coal C which is resistant to chemical reaction. The quantity of coal C can then be determined by normal combustion procedures from the treated sample.

Uncertainties in measuring and detecting changes in SOC pools are high both at individual sites and extrapolating site level data to larger scales due to inherently variable SOC pools both spatially and temporally. This variability makes it difficult to detect the pool response to management practices. An abundance of stones encountered in mine spoils can also impede measurement of site level soil pools. Accurate and precise approaches must be available for assessing the change in SOC in the minesoils if this pool is to be adopted as part of any future accounting system. The Kyoto protocol, for example, limits reporting of C sequestration activities to those that are "measurable and verifiable." A successful accounting will require standardized, simple, reproducible approaches that can be used by resource managers and policy makers outside the research community for validating C sequestration.

X. GLOBAL POTENTIAL OF SOIL ORGANIC CARBON SEQUESTRATION IN MINESOILS

Coal accounts for 24 percent of total energy consumed globally, making it the second largest source of primary energy. There are an estimated 11 Eg of coal reserve globally, about 80 percent of those resources are found in Russia and the former Soviet Republics, United States, and China (Mitsch and Jorgensen, 2004). Global coal consumption in year 2002 was 4.8 Pg, and it is projected to increase by 1.5 percent per yr for the next 20 years (Table 1; EIA 2004). Major coal-consuming countries include the United States, and China; in total they account for about 50 percent of the world's coal consumption (EIA, 2004). Although coal is an important source of energy, its mining activities disturb both soils and the terrestrial ecosystem. When surface mining is used for coal extraction, a great expanse of landscape is disrupted. The negative impacts of coal mining in increasing greenhouse effects can include CO_2 emission from decomposition of the OM exposed by land disturbance, coal combustion, and fell biomass.

Global data on land area disturbed by surface mining activities is scarce. In India, it has been reported that for every million tons of coal extracted by surface mining, about 4 ha of land is damaged, and the coal industry renders an area of 1,400 ha yr^{-1} biologically unproductive (Ghose, 2001). In the United States, coal extracted from nearly 745 surface mines operating in 2002 increased 25 percent between 1992 and 2002 from 590 million tons (535 Tg) to 740 million tons (671 Tg) (NMA, 2004). In Ohio, total area disturbed by coal mining between 1977 and 2000 was 25,918 ha (OSM, 2002), while the land disturbed prior to July 1, 1977 needing reclamation in Ohio was 110,872 ha (Lal et al., 2004). In the U.S.A. the total area disturbed by surface mining between 1977 and 2000 was nearly 617,327 ha (OSM, 2002), and a total area of 632,801 ha was disturbed before July 1, 1977 and remains unreclaimed (Lal et al., 2004). Thus, total area disturbed by coal mining in the U.S. is approximately 1.25 Mha.

Using the SOC sequestration rates reported in Table 2 we calculated the 25-year SOC sequestration potential of minesoils of Ohio and the United States. The SOC sequestration potential for Ohio minesoils ranges from 0.68 to 6.33 Tg C with an average of 3.50 Tg C. The SOC sequestration potential for reclaimed minesoils in the United States ranges from 6.25 to 57.8 Tg C or an average of 32.0 Tg C, at the rate of 1.28 Tg C yr^{-1}. The U.S. average emissions from coal combustion from 1990 to 2002 were 506 Tg C yr^{-1} (USEPA, 2004). Therefore, C emissions from coal combustion in the United States are more than 395 times higher than the potential for SOC sequestration in the U.S. minesoils. However, there is an additional C sequestration potential related to aboveground biomass accumulation occurring in trees, shrubs and grasslands, which could increase the C sequestration in reclaimed minesoil ecosystem.

XI. SUMMARY AND CONCLUSIONS

The reported rates of C sequestration in minesoils vary with soil depth, time since reclamation and land use. The capacity of soils to sequester SOC is finite, the rate of SOC sequestration decreases with duration since reclamation. However, the time required for SOC to reach steady-state or new equilibrium level remains uncertain. The rate of SOC sequestration is generally higher for surface soils and decreases with soil depth, with a range of 0.5 to 1.85 Mg ha^{-1} yr^{-1} for 0–15 cm depth and 0.2 to 1.2 Mg ha^{-1} yr^{-1} for 15–30 cm depth. The potential of SOC sequestration in minesoils of the United States is estimated at 1.28 Tg C yr^{-1}. However, afforestation coupled with recommended management practices could increase C sequestration in the biomass, and contribute significantly to mitigating CO_2 emissions.

There is a sizeable potential of successful reclamation of minesoil and SOC sequestration improvement by applying biosolids and coal combustion by-products as both nutrients source and soil amendments. However, these by-products also have potentially deleterious consequences if used improperly. Research is needed to understand their interactions with minesoils in different mineralogical, geochemical and hydrological settings. Determination of C concentration in the minesoils is complicated by presence of substantial amount of coal which is difficult to differentiate from recently deposited C from the organic material in the routine laboratory analysis. Currently there is no recommended method for separating coal C and recent SOC. In addition, there are no standardized sampling protocols for minesoils. This makes the estimates of minesoil C pools which are estimated based on individual sites less reliable.

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