

Soil Organic Carbon Sequestration in Reclaimed Minesoils

V. A. Akala (akala.1@osu.edu; 614-439-8457)
Rattan Lal (lal.1@osu.edu; 614-292-9069)
School of Natural Resources
The Ohio State University
2021 Coffey Road, 210
Columbus, OH 43210

Abstract

Land disturbance during mining results in loss of soil organic carbon (SOC). Reclamation of minelands can lead to recuperation and sequestration of SOC. The SOC thus accumulated, not only replenishes SOC losses but may also offset additional carbon di-oxide (CO₂) emission. The assessment of the above was done on a chronosequence of reclaimed minesoils comprising pasture with topsoil application. The chronosequence consisted of reclaimed mine sites, 0 to 25 years old, keeping 1997 as the base year. The data show that there was a drastic loss of SOC during mining, and minesoil reclamation over time enhanced SOC pools to original levels. The SOC dynamics in soil macro and micro-aggregate fractions and its effect on long-term carbon (C) sequestration are discussed.

Introduction

Carbon (C) management in the next century will probably be the single most important challenge in the context of the enhanced greenhouse effect. Houghton et al., (1996) predicted that carbon dioxide (CO₂) emission to the atmosphere would increase from 7.4 Gigatons (Gt) C per year (GtC yr⁻¹) (1Gt = 1 Petagram (Pg) = 10¹⁵ g) in 1997 to approximately 26 GtC yr⁻¹ by 2100. Although the effects of increased CO₂ levels on the functioning of ecosystems and energy systems is uncertain, many scientists agree that a doubling of atmospheric CO₂ concentrations could have a variety of serious environmental consequences (Barnett and Schlesinger, 1987; Lindzen, 1994; Santer et al., 1995; Adams et al., 1999). Technical ways to manage C include: (i) efficient use of

energy (ii) increased usage of low-C or C-free fuels and renewable energy, and (iii) capturing and securely storing carbon emitted from the global energy system (C sequestration) (USDOE, 1999). Carbon forms that can be stored include CO₂, elemental C and mineral sources that contain C from known sources. Soil C sequestration is one of the important mechanisms wherein C storage in soil is enhanced and its loss minimized, thereby reducing the rate of increase of atmospheric concentration of CO₂.

The terrestrial ecosystem is a major biological scrubber for atmospheric CO₂ (present net carbon sequestration is 2 GtC yr⁻¹) that can be significantly increased by careful management over the next 25-30 years (Beran, 1995). Two among the most important sinks for C in the terrestrial ecosystem are the biosphere and the pedosphere. The potential of the pedosphere to sequester C can play an important role in the overall management of C (Schlesinger, 1990; Goudriaan, 1995; Paul et al., 1997; Potter and Klooster, 1997; Trumbore, 1997; Lal et al., 1998; Lal, 1999; Marland and Schlamadinger, 1999; Rosenberg et al., 1999; Rosenzweig and Hillel, 2000). The SOC pools form the largest sink in the terrestrial ecosystem after sedimentary rocks and fossil deposits. It is, however, this pool that is most vulnerable to disturbance. Therefore, practices and management efforts that retain SOC, lead to C sequestration and can bring about reduction in greenhouse effect (Schlamadinger and Marland, 2000).

Terrestrial ecosystems, specifically plants and the pedosphere can be effective sinks, though the long-term conversion of grassland and forestland to cropland (and grazing lands) has resulted in historic losses of soil C worldwide (Houghton et al., 1983; Bouwman, 1990; Wallace, 1994; Houghton, 1995). However, there is a major potential for increasing SOC through restoration of degraded soils and widespread adoption of soil

conservation practices, an issue addressed by SOC sequestration (Johnson and Kern, 1991; Lal and Kimble, 1997; Lal and Bruce, 1999). In contrast, however, soil inorganic carbon (SIC) sequestration is the immobilization of C in the form of pedogenic (secondary) carbonates, and leaching of carbonates and bicarbonates into the ground water. The SIC sequestration may be the significant pathway of C sequestration in arid and semi-arid regions (Lal et al., 2000). This discussion is limited to SOC sequestration in relation to mine soils (with topsoil application) reclaimed under pasture.

Mineland reclamation and SOC sequestration

Mining causes extensive change to the original soil profile. During the process of mining, the topsoil (0 to 0.5m) is removed and stored separately. The overburden, which comprises of rock and heavy geologic material on top of the ore body, is then removed and placed into already mined pits. During the process of reclamation the overburden is graded, before the stored topsoil is applied on top of the overburden to a depth of 0.25 to 0.3 m. The topsoil is also graded to approximate the original or adjoining contour of the land. Initial dose of fertilizers and mulch is then applied before seeding the land with a mixture of grasses, legumes and forbs. Minesoil, therefore, is a mixture of soil and spoil or overburden that is being managed and reclaimed. The characteristics, processes and mechanisms occurring in minesoils differ from those prior to mining and disturbance. The land under reclamation essentially remains undisturbed. The land may be put into use after the release of phase I bond, the time period of which may vary between 2 to 4 years after initial seeding.

SOC sequestration depends on factors and processes that determine net primary productivity and its addition to the soil body, and those that affect soil organic matter

(SOM) accretion and decomposition in the soil. Changes in SOC content reflect the net result of C input (via plant litter) and C loss (via decomposition). To elicit a gain in C storage, therefore, there must be an increase in the amount of C entering the soil as plant residues, and suppression in the rate of SOM decomposition. These two processes, and hence SOC cycling and storage, are controlled by complex underlying biotic and abiotic interactions and feedbacks. Primary productivity and decay of SOM are influenced by the five state factors related to soil formation (Jenny, 1980), many of which are sensitive to management practices. The interdependency of primary productivity and SOC content in the soil is the core of SOC cycling and sequestration (Stevenson, 1994). Realizing the potential of soil as a sink for C requires understanding of soil processes that effect SOC sequestration.

Reclamation of mineland, therefore, leads to the establishment of biomass, which in turn results in the accretion of SOM to the developing minesoil. Thus, the rationale of the study was that the temporal changes in minesoil processes in relation to biomass addition could lead to SOC sequestration. Specifically, the hypothesis was that SOC sequestration is a function of time and soil aggregation.

Based on the above hypothesis, the objectives of the study were to:

1. Determine temporal changes in SOC content and
2. Assess SOC dynamics in relation to one of the important soil processes, namely soil aggregation.

Methodology

The study area comprised reclaimed minelands in Morgan, Muskingum and Noble counties of Ohio, USA. The reclaimed minelands are owned and operated by

American Electric Power (AEP). Soil samples for 0-15 and 15-30 cm depths were obtained during 1997 from reclaimed minelands under pasture treatment. The year 1997 was the reference or baseline year. A chronosequence of 0, 5, 10, 15, 20, and 25-year-old reclaimed sites corresponding to reclamation since 1997, '92, '87, '82, '77, and '72, respectively, were chosen for the study. Surface mining was, and is a predominant land use in southeastern Ohio. Shallow seams of coal were mined in the 1930s and 1940s and voluntarily reclaimed to forest. Current mining technology makes deep mining feasible and economical, and therefore, land that were reclaimed in the 1930s and 1940s are again being mined. Hence, undisturbed ecosystems are rare. Therefore, the reclaimed pasture sites were compared to a 70-year-old marginal agricultural land under pasture, which is referred to as the pasture control site in the study. The losses and gains in SOC pools of the reclaimed sites in the study should thus be considered in the context of the above-mentioned control site. In order to reduce variation in spoil (overburden) characteristics, criteria for choosing the sampling sites included similar topography, geologic strata, and coal mining procedure.

There were three sampling locations for each of the reclaimed and control sites or years. Within each sampling location, three sub-samples were obtained for each of the sampling depths. The three sub-samples from each depth were mixed to form one composite sample. The composite soil samples were sieved to separate whole soil (< 2 mm) and soil aggregates (5 mm to 8 mm). The whole soil was utilized for the analysis of total SOC content and the soil aggregates were used to determine the aggregate size distribution of SOC. The aggregate size fractions (represented as % by weight) of 5-8 mm, 2-5 mm, 1-2 mm, 0.5-1 mm and 0.25-0.5 mm were obtained by wet sieving (Yoder,

1936). The SOC content of the whole soil and that associated with soil aggregate fractions was determined by dry combustion (Nelson and Sommers, 1986; USDA, 1996). The whole soil or total SOC content was calculated using the following equation (Lal et al., 1998):

$$\text{MgC ha}^{-1} = [\% \text{ C} * \text{Corrected } \rho_b * d(\text{m}) * 10^4 \text{ m}^2 \text{ ha}^{-1}] / 100$$

where MgC ha^{-1} = Mega gram carbon per hectare ($1 \text{ Mg} = 10^6 \text{ g}$), ρ_b (Mg m^{-3}) = soil bulk density (Mega gram per cubic meter), and d = depth in meters. The SOC pool associated with soil aggregate fractions was calculated as g kg^{-1} (grams carbon per kilogram of soil). Significant differences in SOC pool between the reclamation duration and fractions were calculated as least significant difference (LSD) with a probability level of $\bullet 0.05$. The statistical package MINITAB (v13.1) was utilized to perform all the statistical tests (Minitab, 2000).

Results and discussion

Total Soil Organic Carbon: The total SOC content increased over the reclamation duration for both depths and treatments. Minesoils developed recognizable horizonation in relatively short period of time (10-15 years). The upper horizon (0 to 0.03 m) primarily consisted of undecomposed litter and partially decomposed SOM. The 0.03 to 0.1 m comprised of dark layer of soil, visibly showing SOC accretion. The 0.1 to 0.25 m layer was comparatively light colored with interspersed roots. The layers below 0.25 m primarily consisted of rock overburden that had limited root presence.

The SOC content increased from 9.2 Mg ha^{-1} in the beginning of reclamation period to 55.4 Mg ha^{-1} after 25 years for the 0-15 cm depth and from 7.8 Mg ha^{-1} to 37.8 Mg ha^{-1} for the 15-30 cm depth (Figure 1 and 2 respectively). The SOC content of the

pasture control site were 30.3 Mg ha⁻¹ and 14.7 Mg ha⁻¹ for 0-15 cm and 15-30 cm depths, respectively. Temporal change in losses and gains in the SOC contents of reclaimed sites with respect to the pasture control site over the reclamation duration are shown in Figures 1 and 2 for 0-15 cm and 15-30 cm depths, respectively. In comparison to an initial loss of 21 Mg ha⁻¹, there was a gain of 25 Mg ha⁻¹ after 25 years for the 0-15 cm depth. Similarly, there was a loss of 7 Mg ha⁻¹ followed by a gain of 23 Mg ha⁻¹ after 25 years for the 15-30 cm depth. It is, however, important to note that the magnitude of the loss and gain depend on the SOC content of the control site. There was significant difference in SOC content of the pasture control site and 25-year-old reclaimed sites for both depths.

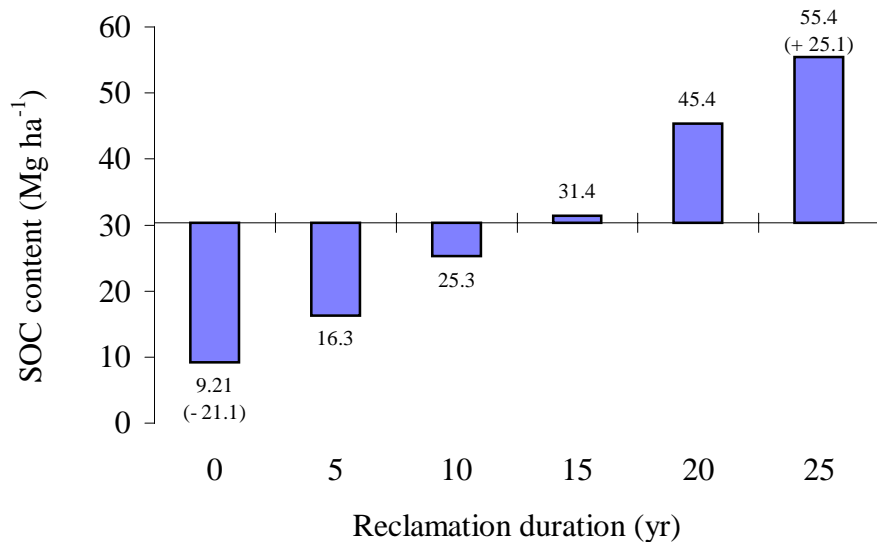


Figure 1. Temporal change in total soil organic carbon (SOC) content of pasture treatment for 0-15 cm depth. (The x-axis is placed at the SOC content of the pasture control site for 0-15 cm depth. Values shown are SOC contents. Values in brackets are loss (-) or gain (+) in SOC content.)

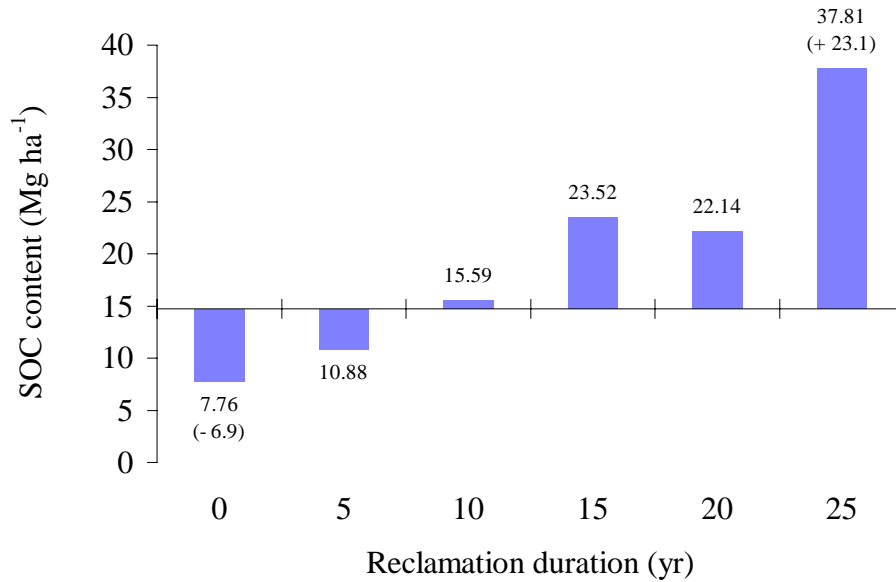


Figure 2. Temporal change in total soil organic content (SOC) content of pasture treatment for 15-30 cm depth. (The x-axis is placed at the SOC content of the pasture control site for 15-30 cm depth. Values shown are SOC contents. Values in brackets are loss (-) or gain (+) in SOC content.)

Soil Aggregation and SOC distribution:

Soil aggregates were classified as macroaggregates (> 0.25 mm) and microaggregates (< 0.25 mm). Soil macroaggregation increased and microaggregation decreased over the period of reclamation. During mining, the soil macroaggregates that were originally present in the soil may have degenerated to form microaggregates due to physical forces of mining and loss of SOC. However, during the course of reclamation, soil microaggregates may have come together in the presence of SOC (biomass input during reclamation) to form soil macroaggregates.

Soil macroaggregation increased from 24.2 % to 60.9 % and microaggregation decreased from 56.6 % to 20.0 % over the 25 years period for 0-15 cm depth. For the 15-30 cm depth, macroaggregation increased from 58.2 % to 64.4 % and microaggregation decreased from 26.1 % to 20.0 % during the same time period. Soil aggregation of the

pasture control site was 77.6 % in the macroaggregate fraction and 19.5 % in the microaggregate fraction for the 0-15 cm depth, and 67.9 % and 12.2 %, respectively for the 15-30 cm depth. The SOC content of the macroaggregate fraction increased from 3.0 g kg⁻¹ to 17.3 g kg⁻¹ and that of the microaggregate fraction increased from 1.3 g kg⁻¹ to 7.0 g kg⁻¹ for the 0-15 cm depth. For the 15-30 cm depth, the SOC content of the macroaggregate fraction increased from 4.0 g kg⁻¹ to 12.4 g kg⁻¹ and that of the microaggregate fraction remained fairly constant. The SOC content of the pasture control site was 15.2 g kg⁻¹ in the macroaggregate fraction and 0.2 g kg⁻¹ in the microaggregate fraction for 0-15 cm depth, and 7.4 g kg⁻¹ and 0.2 g kg⁻¹ respectively, for 15-30 cm depth.

Temporal change of gains and losses (in comparison to the pasture control site) in SOC content and soil aggregation of the macro and micro-aggregate fractions for 0-15 cm depth are shown in Figure 3. From an initial loss of 53.4 % in macroaggregation, the loss decreased to 16.7 % in 25 years (Figure 3a). Loss in macroaggregation also led to the loss of SOC pool. From an initial loss of 12.2 g kg⁻¹, there was gain of 2.1 g kg⁻¹ after 25 years (Figure 3a). From an initial increase in microaggregation by 37.1 % during the initial phase, it decreased to 0.4 % after 25 years (Figure 3b). The increase in microaggregation during the initial phase emphasized the disturbance caused by mining and the decrease during the latter part of the reclamation period showed that the action had shifted towards the formation of macroaggregates. The SOC content for the microaggregate fraction remained almost constant over the reclamation duration (Figure 3b). This showed that the SOC pool associated with the microaggregate fraction remained stable.

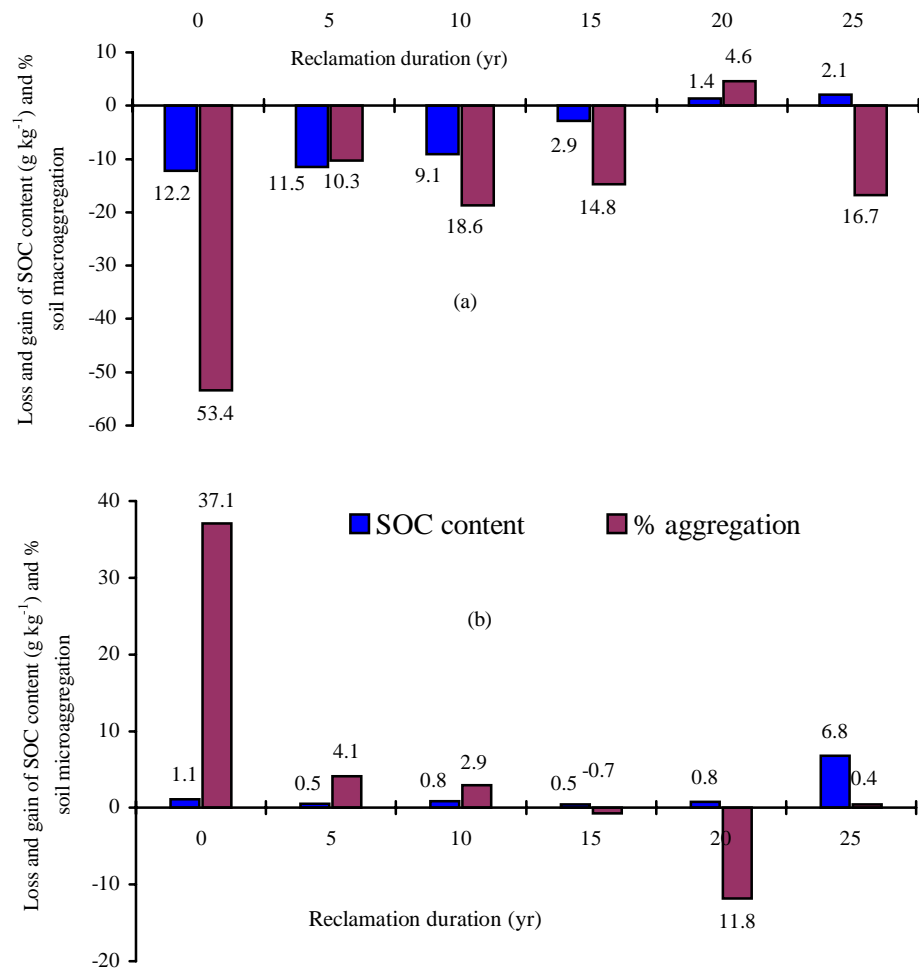


Figure 3. Temporal loss and gain in soil organic carbon (SOC) content and soil aggregation (compared to pasture control site) in (a) macroaggregate and (b) microaggregate fractions of pasture treatment for 0-15 cm depth

For the 15-30 cm depth, the temporal change in gains and losses (in comparison with the pasture control site) in SOC content and soil macro and micro-aggregation are shown in Figure 4. In the macroaggregate fraction, the loss in aggregation was highest during the initial phases of reclamation (highest being 21.9 % for the 10 year old site), which decreased to 3.4 % in 25 years (Figure 4a). There was a loss of SOC content in the initial phase of reclamation (maximum being 5.1 g kg⁻¹ for the 5 year old site) but there was a gain of 4.9 g kg⁻¹ in 25 years (Figure 4a). From an initial increment in microaggregation by 13.8 % during the initial phase, it decreased to 7.8 % after 25 years (Figure 4b). The changes in SOC content remained somewhat constant over the reclamation duration (Figure 4b). The data show that macroaggregation in the reclaimed sites was getting close to that of the control sites. In addition, temporal changes in soil aggregation and SOC accumulation in the macroaggregate fraction was predominant in the 0-15 cm depth and was considerably low for the 15-30 cm depth.

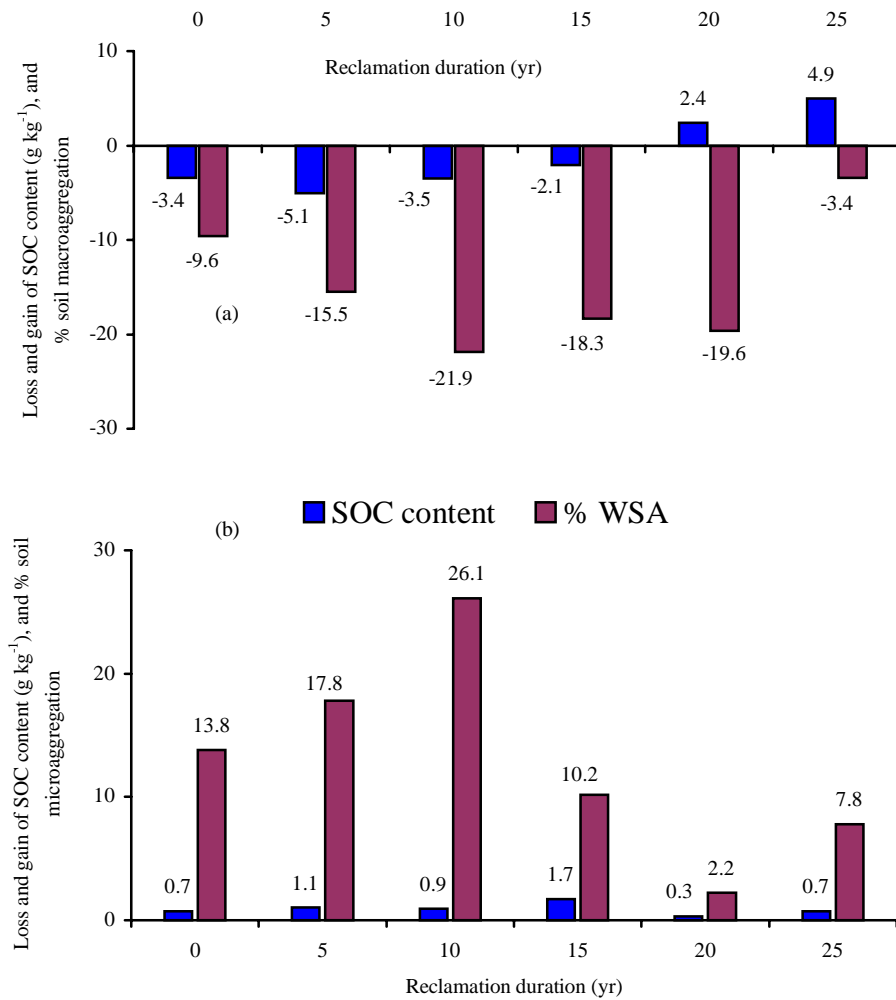


Figure 4. Temporal loss and gain in soil organic carbon (SOC) content and soil aggregation (compared to pasture control site) in (a) macroaggregate and (b) microaggregate fractions of pasture treatment for 15-30 cm depth

Conclusion

Reclaimed minesoils show a positive potential to sequester SOC. The SOC pools that accumulate in such systems are comparable to that of no-till systems and wetlands and in some instances are higher. This may be due to judicious land management and long periods of undisturbed state of the reclaimed land. The loss of SOC due to the

degenerative effect of mining continues during the initial stages of reclamation. SOC buildup starts after 5 to 10 years of reclamation and depends on the biomass growth and input. This study can be used as a basis to understand the potential of SOC sequestration in disturbed lands, provided that disturbed lands are subject to land restoration.

It is important, however, to maintain the stability of the soil in order for SOC to remain sequestered within soil aggregates. Soil macroaggregates are vulnerable to disturbance and are structurally less stable, but have the potential to physically and to some extent chemically bind SOM, thereby limiting the decomposition of SOC. Soil microaggregates (that are essentially the building blocks of the soil macroaggregate matrix) on the other hand retain SOC in a way that is comparatively less susceptible to physical disturbance. Therefore, the interplay of factors that include SOC accretion, formation of macroaggregate matrices, time and land management lead to SOC sequestration.

The study also showed that mineland reclamation could accrue SOC sequestration levels that are more than that of undisturbed lands. This may be due to change in land use (because soil that was initially under forest was now under pasture) or increase in the inherent capacity of the soil to sequester carbon. Careful land management and use can optimize the latter. SOC sequestration, therefore, can be used as a mechanism to not only gain environmental and agronomic benefits but can be used as a technology to mitigate green house gases. However, criteria for SOC pools, its verification, long term benefits and policy implications are some of the important areas that need further research.

Acknowledgement

The Office of Solar Thermal, Biomass Power, and Hydrogen Technologies within the Office of Utility Technologies, U.S. Department of Energy with Lockheed Martin Energy Research Corporation sponsored this research. Special thanks to Messers Mark Downing, Paul Loeffelman, Tom Archer, Gary Kaster and Art Boyer of American Electric Power (AEP). This study was part of PhD research of the author and conducted under the supervision of Dr. Rattan Lal, School of Natural Resources, The Ohio State University.

References

- Adams, R.M., B.H. Hurd and J. Reilly. 1999. Agriculture and global climate change: A Review of Impacts to U.S. Agricultural Resources. The Pew Center on Global Climate Change, Arlington, VA.
- Barnett, T.P. and M.E. Schlesinger. 1987. Detecting changes in global climate induced by greenhouse gases. *J. Geophys. Res.* 92:14772-14780.
- Beran, M.A., (ed.) 1995. Carbon sequestration in the biosphere: Processes and Prospects. Springer. New York, NY. pp. 304.
- Bouwman, A.F. 1990. Exchange of greenhouse gases between terrestrial ecosystems and the atmosphere. p. 1-9. *In* Soil and greenhouse effect. A. F. Bouwman (ed.). John Wiley and Sons, New York, NY.
- Goudriaan, J. 1995. Global carbon cycle and carbon sequestration. NATO ASI Series 1, 30:3-18.
- Houghton, R.A. 1995. Changes in storage of terrestrial carbon since 1850. p. 45-65. *In* Soils and global change. R. Lal, J. Kimble, E. Levine and B. A. Stewart (eds.). CRC Press Inc., Boca Raton, FL.
- Houghton, R.A., J.E. Hobbie, J.M. Mellilo, B. Moore, B.J. Peterson, J.R. Shaver and G.M. Woodwell. 1983. Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: a net releaser of CO₂ to the atmosphere. *Ecol. Monogr.* 53:(3)235.

- Houghton, J.T., L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg and K. Maskell, (eds.). 1996. *Climate change 1995: The Science of Climate Change: Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, U.K.
- Johnson, M.G. and J.S. Kern. 1991. *Sequestering C in soils: A workshop to explore the potential for mitigating global climate change*. USEPA Environmental Research Laboratory, Corvallis, OR.
- Jenny, H. 1980. *The soil resource: Origin and Behavior*. Springer-Verlag, New York, NY.
- Lal, R. 1999. Soil management and restoration for C sequestration to mitigate the accelerated greenhouse effect. *Prog. Environ. Sci.* 1:307-326.
- Lal, R. 2000. Soil aggregation and C sequestration. p. 317-329. *In Global climate change and tropical ecosystems*. R. Lal, J. M. Kimble and B. A. Stewart (eds.). CRC Press, Inc., Boca Raton, FL.
- Lal, R. and J.M. Kimble. 1997. Conservation tillage for carbon sequestration. *Nutr. Cycl. Agroecosyst.* 49:243-253.
- Lal, R. and J.P. Bruce. 1999. The potential of world cropland soils to sequester C and mitigate the greenhouse effect. *Environ. Sci. Policy.* 2:77-185.
- Lal, R., J.M. Kimble, R.F. Follett and C.V. Cole. 1998. The potential of U.S. cropland to sequester carbon and mitigate the greenhouse effect. Ann Arbor Press, Chelsea, MI. pp.128.
- Lindzen, R.S. 1994. On the scientific basis for global warming scenarios. *Environ. Pollut.* 83:125-134.
- Marland, G. and B. Schlamadinger. 1999. Carbon sequestered, carbon displaced and the Kyoto context. *Proc. TAPPI Int. Environ. Conf.* 1:283-289.
- Minitab. 2000. MINITAB 13.1. Minitab Inc., State College, PA.
- Nelson, D.W. and Sommers, L.E. 1986. Total C, organic C, and organic matter. p 961-1010. *In* A. Klute (ed.) *Methods of soil analysis*. Part 3. ASA, Madison, WI.
- Paul, E.A., K. Paustian, E.T. Elliott and C.V. Cole, (eds.). 1997. *Soil Organic matter in temperate agroecosystems: Long term experiments in North America*. CRC Press. Boca Raton, FL. pp. 430.

- Potter, C.S. and S.A. Klooster. 1997. Global model estimates of carbon and nitrogen storage in litter and soil pools: response to changes in vegetation quality and biomass allocation. *Tellus, Ser. B.* 49B:1-17.
- Rosenberg, N.J., R.C. Izaurralde and E.L. Malone, (eds.). 1999. *Carbon Sequestration in Soils: Science, Monitoring, and Beyond.* Battelle Press. Columbus, OH. pp. 199.
- Rosenzweig, C. and D. Hillel. 2000. Soils and global climate change: Challenges and opportunities. *Soil Sci.* 165:47-56.
- Santer, B.D., K.E. Taylor, T.M.L. Wigley, J.E. Penner, P.D. Jones and U. Cubasch. 1995. Towards the detection and attribution of an anthropogenic effect on climate. *Climate Dynamics.* 12:77-100.
- Schlamadinger, B. and G. Marland. 2000. Land use and global climate change: Forest, Land management, and the Kyoto Protocol. *Pew Center of Global Climate Change, Arlington, VA.* pp. 54.
- Schlesinger, W.H. 1990. Evidence from chronosequence studies for a low carbon-storage potential of soils. *Nature.* 348:(6298)232-234.
- Stevenson, F.J. 1994. *Humus chemistry: Genesis, Composition, Reactions.* Wiley, NY. pp.496.
- Trumbore, S.E. 1997. Potential responses of soil organic carbon to global environmental change. *Proc. Natl. Acad. Sci.* 94:(16)8284-8291.
- United States Department of Agriculture (USDA), Natural Resource Conservation Service (NRCS). 1996. *Soil Survey Laboratory methods manual.* pp. 693.
- United States Department of Energy (USDOE). 1999. *Carbon Sequestration: State of the Science, A working paper for road mapping future carbon sequestration R&D.* USDOE, Washington, D.C.
- Yoder, R.E. 1936. A direct method of aggregate analysis and a study of a physical nature of erosion losses. *J. Am. Soc. Agron.* 28:337-351.
- Wallace, A. 1994. Soil organic matter must be restored to near original levels. *Commun. Soil Sci. Plant Anal.* 25:29-35.