FINAL REPORT

Midwest Regional Carbon Sequestration Partnership
2005 - 2010
Phase II Final Report on Carbon Sequestration in Croplands

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MRCSP
MIDWEST REGIONAL
CARBON SEQUESTRATION
PARTNERSHIP

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TABLE OF CONTENTS

APPENDICES

LIST OF TABLES

LIST OF FIGURES

ACRONYMS

COMMONLY USED ABBREVIATIONS IN SOIL SCIENCE AND CARBON MANAGEMENT

ANOVA : Analysis of Variance
As : Arsenic
B : Boron
BAU : Business-as-Usual
BC : Black Carbon
BD : Bulk Density
BECS : Bioenergy Crops with Sequestration
BTU : British Thermal Unit
C : Carbon
C/N : Carbon to Nitrogen ratio
Ca : Calcium
$CaCO_3$: Calcium Carbonate
CBA : Cost Benefit Analysis
CBM : Cost Benefit Analysis
CCS : Carbon Capture and Storage
CCX : Chicago Climate Exchange
CEC : Cation Exchange Capacity
CFI : Carbon Finance Instruments
Cl : Chlorine
CMASC : Carbon management and sequestration center
CO_2 : Carbon Dioxide
CP : Chisel plow
CT : Conventional Tillage
Cu : Copper
DAI : Dangerous Anthropogenic Interference
DIC : Dissolved Inorganic Carbon
DOC : Dissolved Organic Carbon
DOE : Department of Energy
EC : Electrical Conductivity
EOR : Enhanced Oil Recovery
EPA : U.S. Environmental Protection Agency
Fe : Iron
g : Gram
GHG : Greenhouse Gas
GIS : Global Information Systems
GPP : Gross Primary Productivity
GWP : Global Warming Potential
GWR : Geographically weighted regression
H : Hydrogen
H_2O : Water
Ha : Hectare

HSD : Honest Significant Difference
HTT : Highest Treatment Temperature
INM : Integrated Nutrient Management
IOR : Improved Oil Recovery
IPCC : Intergovernmental Panel on Climate Change
K : Potassium
$\boldsymbol{K}_{\mathbf{sat}}$: Saturated hydraulic conductivity
L : Liter
Lb : Pound
LCA : Lifecycle Analysis
LIHD : Low-Input High-Diversity Crops
m : Meter
MF : Mycorrhizal Fungi
Mg : Megagrams (10^6 grams)
Mha : Million hectares
MLR : Multiple linear regression
MLRA : Major land resource area
Mn : Manganese
MP : Moldboard plow
MRCSP : Midwest Regional Carbon Sequestration Partnership
MRT : Mean Residence Time
N : Nitrogen
Na : Sodium
NBP : Net Biome Productivity
NECB : Net Ecosystem Carbon Balance
NGCC : Natural Gas Combined Cycle
$\mathbf{NH_4}$: Ammonium
NT : No-Tillage
O : Oxygen
OARDC : Ohio Agriculture Research and Development Center
OK : Ordinary kriging
OM Organic matter
OSU : The Ohio State University
PAH : Polyaromatic Hydrocarbon
$\boldsymbol{\rho}_{\mathbf{b}}$: Soil bulk density
PC : Pulverized Coal
Pg : Petagrams (10^{15} grams)
ppm : Parts Per Million

RGGI : Regional Greenhouse Gas Initiative
RK : Regression kriging
RMP : Recommended Management Practices
RO : Rotational tillage
S : Sulfur
SAS : Statistical Analysis Software

Si	:	Silicone
SIC	:	Soil Inorganic Carbon
SOC	:	Soil organic carbon
SOCP	:	Soil Organic Carbon Pool
SOM	:	Soil Organic Matter
Tg	:	Teragrams (10^{12} grams)
TOR	:	Tertiary Oil Recovery
TRT	:	Treatment
USDA	:	United States Department of Agriculture
VCS	:	Voluntary Carbon Standard
WHC	:	Water Holding Capacity
WL	:	Woodlots
wt	:	Weight
yr	:	Year
Zn	:	Zinc

1. EXECUTIVE SUMMARY

The Midwest Regional Carbon Sequestration Partnership (MRCSP)[1] was established in 2003 as one of seven partnerships in the U.S. Department of Energy's Carbon Sequestration Program to assess the potential of carbon (C) sequestration and strategies for mitigating carbon dioxide (CO_2) emissions. Phase II of the MRCSP program includes conducting small scale field validation tests of selected sequestration technologies. One of the selected field validation tests was to assess the potential for carbon sequestration in croplands for the MRCSP region. The croplands project was carried by the Carbon Management and Sequestration Research Center at The Ohio State University (OSU) under subcontract to Battelle, DOE's prime contractor for the MRCSP. The specific objectives of the croplands research and the Phase II report presented here are to: (i) assess the effects of different land use types on soil organic carbon (SOC), (ii) assess the profile distribution of SOC to determine the C storage within the topsoil and subsoil, and relate it to soil components (particle and aggregate size fractions), (iii) evaluate historic C loss and assess the old vs. new C in soil, and (iv) to estimate the SOC pool for the Midwestern region using geographical information systems (GIS) modeling approaches.

This unique study involved the most extensive soil sampling to date covering an entire region for assessing land use and management effects on SOC and soil quality. In particular, farmers' fields were sampled as no experimental research plots were available to cover the variability in soil properties and climates across the MRCSP region. In contrast to research plots, the plots on farmer's fields are therefore not exactly similar but comparable with respect to land use (e.g., crop rotation) and soil management (e.g., tillage management, fertilization). The information collected from test plots also were used to evaluate various scaling procedures to relate SOC changes for individual field plots to a regional scale via GIS.

This report documents the results of the following Phase II terrestrial field validation tests in croplands:

- The conversion of conventional till (CT) to no-till (NT) practices does not necessarily result in higher SOC concentrations and pools in soil profiles (Chapter 4). Specifically, while SOC generally increased in surface soil horizons for NT because of less disturbance resulting in lower residue and SOC decomposition, the SOC dynamics in deeper horizons after conversion CT to NT were variable and depended on soil type and landscape position. Thus, soil samples need to be taken up to 0.5 to 1.0 m depth or ideally the entire rooted soil profile to assess the effects of tillage treatments on profile SOC. However, well-drained soils on sloping landscape positions generally had higher profile SOC after conversion CT to NT. Most importantly, the effects of tillage on SOC and soil quality cannot be generalized for the entire MRCSP region as effects are soil type specific
- Another MRSCP study indicated that retention of wheat straw in NT practices increased aggregate tensile strength, and SOC, and retained higher moisture levels (Chapter 5). The annual rate of C sequestration was 1.2 Mg ha^{-1}, with the mean of wheat straw converted

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[1] The MRCSP region originally consisted of seven contiguous states: Indiana, Kentucky, Maryland, Michigan, Ohio, Pennsylvania, and West Virginia. New York became a member state in 2007 and New Jersey in 2009.

into SOC being ~ 33%. These data strongly suggest that long-term straw mulching increased SOC concentration, improved near-surface aggregation, and improved crop yields.

- The MRSCP conducted a study on the effects of corn (*Zea mays* L.) stover removal for bioenergy on soil properties (Chapter 6). To minimize detrimental effects on soil quality at the studied sites, the removal rates must be lower than 1.25 Mg ha^{-1} yr^{-1}. However, this removal rate is not applicable to the entire MRSCP region as site-specific adjustments are required.
- Further, combining CT with NT during rotational tillage practices adversely affects the SOC pool and soil physical properties (Chapter 7). Thus, NT has to be maintained to sustain any benefits for SOC and soil quality.
- Another study assessed the effects of cattle grazing during the growing season and, in addition, the dormant season on SOC and soil physical properties (Chapter 8). It was shown that although dormant season grazing reduced soil quality, a mix of seasonal paddocks reduces the pressures by over-grazing on individual sites.
- The results obtained by CMASC as part of this MRCSP funded project about soil erosion indicated that the loss of highly productive topsoil by erosion causes a strong decrease in SOC and soil physical quality (Chapter 9). Thus, land use and management practices causing accelerated soil erosion must be reduced to maintain SOC and agricultural productivity.
- The restoration of degraded soil by planting to tall-grass prairie and effects on SOC and soil physical properties was also studied by CMASC as part of this MRCSP funded project (Chapter 10). The positive effect of tall-grass on SOC and soil quality enhances its potential as bioenergy crop for cultivation on degraded soils.
- GIS was used to assess and model the SOC sequestration potential in the MRCSP region (Chapter 11). An optimum combination of baseline soil C, land use, and management practices can maximize soil C sequestration potential. For state level estimation of C pool and identifying potential regions for C sequestration, less detailed soil maps may be used without compromising data accuracy. Detailed soil maps are useful for sub-county level mapping of SOC. Further, the prediction of SOC and its spatial variability is possible using geostatistical approaches, and the geostatistical methods can be adopted at different scales. Specifically, the geographically weighted regression (GWR) approach can play a vital role in improving the prediction ability of SOC pools across regional scales.

Taken together, the findings from the research described here showed that the quantity and rate of C loss and C sequestration depends on soil type, texture and drainage, tillage intensity, and duration of NT management. A rapid decrease in SOC and nutrients occurs when forest soils are cultivated. The NT management practices potentially restore SOC which was otherwise depleted due to the tillage practices. The NT practices improve the SOC and hence the soil hydraulic properties such as water retention, hydraulic conductivity and pore size distribution compared to mold board plow (MP) and chisel plow (CP). The crop residue left on top of the soil in NT practices improves the soil hydraulic properties. The GIS studies conducted under MRCSP project showed that SOC can be estimated at larger (state and regional) scale.

While, the soil sampling at state and regional scale is expensive and time consuming, the GIS findings showed that surface interpolation methods (e.g., ordinary kriging, multiple linear regression, GWR and regression kriging) can be used to estimate the SOC pool at larger scale. The SOC pool to 50 cm soil depth for the MRCSP region was calculated to be 6.21 Pg. Higher SOC pool in the region was attributed to the high rainfall, low temperature and the presence of Histosols and Mollisols in this region.

The MRCSP Phase II findings report here show that there is an estimated 10.7 million hectares of prime non-eroded cropland present in the MRCSP region. It is estimated that 22.5% of that land area is already practicing no-till and will likely remain in that mode. The remaining 77.5% or 8.3 million hectares is potentially amenable to adopting no-till or reduced tillage practices, which, if adopted on these lands, would result in an estimated 55 to 74 additional teragrams (Tg) of C sequestered over a 20 year period for the MRCSP region. This is equivalent to 200 to 270 Tg of CO_2. Conversion of cropland to NT and reduced tillage practices also yields benefits of placing land use in more sustainable agricultural practice, and reduces emission through diesel consumption used for plowing and other farm operations.

Implication for C credit trading based on the MRSCP terrestrial field validation test in croplands study are that complete life-cycle analyses (LCA) of production systems (i.e., no-till, plow tillage, manuring) must be conducted to assess management-induced changes in ecosystem C pool. The data on changes in ecosystem C pool are essential to developing an effective mechanism for monitoring and verifying SOC on regional scales, which could be utilized by possible offset programs in the future. In particular, up-scaling of the SOC pool can be performed by using GIS and terrain characteristics. This modeling approach is extremely useful in assessing C credits for trading purposes.

2. INTRODUCTION

The MRCSP was established to assess the technical potential, economic viability and public acceptability of carbon sequestration within its region. It is one of seven regional carbon sequestration partnerships established nationwide by the Department of Energy (DOE) as part of its overall strategy to develop robust, cost-effective options to mitigate carbon dioxide (CO_2) emissions that contribute to climate change.

The MRCSP region originally consisted of seven contiguous states: Indiana, Kentucky, Maryland, Michigan, Ohio, Pennsylvania, and West Virginia. New York became a member state in 2007 and New Jersey in 2009. A group of leading universities, state geological surveys, nongovernmental organizations and private companies, led by Battelle, has been assembled to carry out this important research.

The DOE's Regional Carbon Sequestration Program is being implemented in three incremental phases: the Characterization Phase; the Validation Phase; and the Development Phase. MRCSP initiated work in October 2003 under a two-year, Characterization Phase project which focused on developing a comprehensive assessment of CO_2 sources and sequestration opportunities in the MRCSP region. Based on this mapping activity, the MRCSP developed recommendations for several small-scale geologic and terrestrial field tests, which were conducted under the Validation Phase of the program (2005-2010). This report documents the results of the terrestrial sequestration validation field tests in croplands.

A glossary of terms pertinent to terrestrial carbon sequestration is provided in Appendix A.

2.1 Terrestrial Carbon Cycle, Climate Change and Agriculture

The Earth's temperature and the carbon (C) content of the atmosphere are correlated on geological time scales (>100,000 years). The global C cycle describes the biogeochemical cycling of C among the atmosphere, biosphere, hydrosphere, pedosphere and lithosphere on Earth. The C cycle processes take place over hours to millions of years, and a long-term and a short-term C cycle can be distinguished (Berner, 2003). The long-term C cycle, in particular, describes the exchange of C among the rocks and the surficial system consisting of the ocean, atmosphere, biosphere and soil. This cycle is the main controller of the atmospheric carbon dioxide (CO_2) concentration over geological timescale.

The short-term C cycle is of greater importance than the long-term C cycle with respect to C sequestration in terrestrial ecosystems. This cycle controls the atmospheric concentrations of both CO_2 and methane (CH_4) through continuous flows of large amounts of C among the oceans, the terrestrial biosphere and the atmosphere (Denman et al., 2007). Atmospheric C fixed during photosynthesis is returned by plant, microbial and animal respiration, and released to the atmosphere as CO_2 under aerobic, and some as CH_4 under anaerobic conditions. Both CO_2 and CH_4 are greenhouse gases (GHGs), i.e., constituents of the atmosphere that absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth's surface, the atmosphere itself, and by clouds.

The natural fluxes among C pools in the atmosphere, terrestrial biosphere and oceans have been approximately in balance before human activities severely perturbed the natural global C cycle via anthropogenic greenhouse gas emissions. In particular, since the onset of the industrial revolution ~ 1800, CO_2 is added to the atmospheric pool from hundreds of millions of year old geological pools by burning fossil fuels (coal, oil, gas) and by cement production (i.e., heating limestone) (Steffen et al., 2007). Since 1950 the perturbation of the global C cycle has accelerated as human enterprise has experienced a remarkable explosion (Steffen et al., 2007). In addition to fossil fuel burning and cement production, deforestation and agricultural development add CO_2 to the atmosphere from decadal to centuries old pools in the terrestrial biosphere. Deforestation can be defined as clear cutting and conversion of the forest to other land uses such as pastures, crop agriculture, and urban and suburban areas (Asner et al., 2005). It is hypothesized that forest clearance and biomass burning for agriculture 8,000 years ago in Eurasia contributed to the anthropogenic greenhouse era by causing an anomalous increase in atmospheric CO_2 (Ruddiman, 2003). Historically, agricultural soils have lost more than 50 Pg (1 Pg = 10^{15} g) C, and some of this lost C can be recovered through improved agricultural management thereby withdrawing atmospheric CO_2 (Lal, 2004a; Smith et al., 2008). Presently, the net land-atmosphere and ocean-atmosphere CO_2 fluxes are not balanced, and measurable changes in the C pools occurred since pre-industrial times (~10,000 years ago). For example, 140 Pg C have been lost from the terrestrial biosphere through deforestation and agricultural development. Primarily deforestation was responsible for 20% of anthropogenic CO_2 emissions during the 1990s and about 80% resulting from fossil fuel burning (Denman et al., 2007). In 2007, the U.S. were responsible for 19% of the global CO_2 emissions (Guan et al., 2009).

Due to burning of fossil fuels, cement production, deforestation and agricultural development, the atmospheric CO_2 concentration increased from the pre-industrial level of about 280 parts per million (ppm) to a global monthly mean level of 387 ppm in 2009, and is increasing at the rate of about 2 ppm yr^{-1} (Tans, 2010). Global surface temperatures are also increasing but none of the natural processes such as solar variability, El Niño-Southern Oscillation (ENSO) or volcanic eruptions can account for the overall warming trend in global surface temperatures from 1905 to 2005 (IPCC, 2007a; Lean and Rind, 2008). Thus, increasing atmospheric abundance of GHGs (including CO_2 and tropospheric aerosols) has been identified as the source of recent global surface warming or the abrupt climate change or ACC (Allen et al., 2006). An increase in GHGs causes a change in Earth's energy balance or radiative forcing (Shine and Sturges, 2007). Non-CO_2 GHGs have contributed about 1 W m^{-2} to radiative forcing since pre-industrial times but the largest single contributor to radiative forcing is CO_2, contributing about 1.66 W m^{-2} (IPCC, 2007a).

To avert a dangerous degree of ACC, the concentrations of atmospheric CO_2 must be stabilized by mitigation strategies. Avoiding ACC is more easily achievable and more effective by commencing mitigation actions soon (Vaughan et al., 2009). Specifically, the rate of increase in atmospheric CO_2 concentration can be reduced through the process of C sequestration in compartments other than the atmosphere. The term 'carbon sequestration' is defined as the uptake of C containing substances, in particular CO_2, into a long-lived reservoir (IPCC, 2007a). Sequestration is a natural process. Thus, the net flux of -1.15 Pg C yr^{-1} from the atmosphere to the land sink (i.e., in vegetation, detritus and soil) is C sequestration (Sarmiento et al., 2010).

However, fundamental changes in the C cycle may be underway in both the oceans and terrestrial biosphere (Sarmiento et al., 2010).

For climate change mitigation purposes, C sequestration can particularly be defined as the transfer and secure storage of atmospheric CO_2 into other long-lived pools that would otherwise be emitted or remain in the atmosphere (Lal, 2008). These pools are located in the hydrosphere, biosphere, pedosphere and lithosphere. Most important for the short-term C cycle in agricultural ecosystems is the C exchange between these pools and the atmospheric CO_2 pool.

Thus, carbon sequestration in agricultural ecosystems occurs primarily by uptake of atmospheric CO_2 during plant photosynthesis and the subsequent transfer of some fixed C into vegetation, detritus and mostly soil pools for secure C storage.

Terrestrial C sequestration through forestry and agriculture is among the major opportunities to abate global CO_2 emissions (McKinsey&Company, 2009). In particular, forest and agricultural C sequestration is associated with relatively low costs and investments, and can be ramped up relatively fast compared to other abatement opportunities. The key abatement measures in the agricultural sector are (i) land restoration (e.g., re-establishing high water tables to avoid decomposition), (ii) cropland management (including crop rotation, cover crops, tillage reduction, nutrient management), (iii) pastureland management (e.g., increased grazing intensity), and (iv) livestock management. Agricultural emissions from soils in the form of nitrous oxide (N_2O) represent 37% of the agricultural emissions, i.e., 2.3 Pg carbon dioxide equivalent (CO_2e) yr^{-1} as of 2005 (CO_2e is the concentration of CO_2 that would cause the same level of radiative forcing as a given type and concentration of GHG). Thus, terrestrial C sequestration can be increased by sequestering more CO_2 in agricultural soils through changing agricultural practices. For example, conservation tillage/residue management in croplands is estimated to sequester globally between 0.2 and 0.7 Mg (1 Mg = 10^6 g) CO_2e ha^{-1} yr^{-1}. In total, sequestration in agricultural soils may contribute three-quarters to the very large abatement potential by the agriculture sector of 4.6 Pg CO_2e yr^{-1} until 2030. Sequestration would lead to a negative net CO_2e emission from agricultural soils into the atmosphere until 2030 implying that more C will be stored in agricultural soils than will be released. The estimated abatement potential by 2030 for agriculture is large relative to emissions from this sector, and most of the potential would come at a low cost. Eventually, the agricultural C sinks will saturate between 2030 and 2050 as soils build up their maximum C storage potential, and other sequestration measures need to be phased in (McKinsey&Company, 2009).

2.2 Terrestrial Carbon Sequestration in Croplands

The natural buffering mechanisms by which atmospheric CO_2 is transferred into the biosphere and pedosphere must be accelerated to mitigate and adapt to ACC (Macías and Arbestain, 2010). Increased C sequestration can be achieved in terrestrial ecosystems by (i) favoring growth of biomass, (ii) promoting and facilitating carbonation processes, (iii) reducing erosion and favoring pedogenesis, (iv) developing organic matter (OM)-rich horizons, (v) restoring degraded or contaminated soils, and/or (vi) managing waste by use of systems that minimize emissions of GHGs. Carbon sequestration in croplands, in particular, depends on the net C balance among various fluxes which will be discussed in more detail in the following section.

The major input of C into croplands occurs by C fixation during plant photosynthesis and subsequent assimilation into organic compounds (Conant et al., 2007). This process is called gross primary production (GPP) with a global estimate of 14.8 Pg C yr^{-1} for croplands (Beer et al., 2010). A fraction of the fixed C is lost during autotrophic respiration as CO_2, and the bulk of the remaining C or net primary production (NPP) is allocated to the production of crop biomass in foliage, shoots and roots (Ciais et al., 2010). However, because not all of the biomass produced remains on site, direct measurements of total NPP are impossible. Examples of biomass removal processes include crop harvest, and herbivory by insects and mammals. In addition other components of NPP are rarely measured such as weed production, seed production, emission of volatile organic compounds (VOC) to the atmosphere, exudation from roots and C transfer to root symbionts. The sum of all these components is the total cropland NPP (Ciais et al., 2010).

The total rate of organic C accumulation in (or loss from) ecosystems is the net ecosystem carbon balance (NECB) (Chapin et al., 2006). When integrated over time and space the NECB equals the net biome production (NBP). The NBP of croplands can be quantified as:

$$\mathbf{NBP = NPP - R_{h1} - H - D - F - VOC - E + I} \qquad \text{(Eq 1)}$$

Where R_{h1} is the soil heterotrophic respiration (primarily CO_2 but also some CH_4), D is the C flux of photosynthetic origin loss to hydraulic conduits and rivers, F is the C loss to the atmosphere by fire disturbance, H the harvested component of NPP, VOC the NPP component emitted as biogenic volatile organic compounds (VOCs) emissions to the atmosphere, E the flux of C exported from cropland ecosystems by erosion, and I the C input to the soil, e.g., via manure applications (Ciais et al., 2010). Assuming that 100% of H is respired as CO_2 after digestion of crop products by animals and humans, H can be identified to a component of heterotrophic respiration taking place outside ecosystems, called R_{h2}. When summing up the C balance at continental scale, the flux T of respiration by humans and livestock of crop products imported by trade from outside the cropland region must be added. This gives:

$$\mathbf{NBP = NPP - Rh1 - Rh2 - T - D - F - VOC - E + I} \qquad \text{(Eq 2)}$$

The NBP represents the long-term C sequestration in croplands (U.S. DOE, 2008).

Agricultural practices affect (i) the input of C to the soil through manure, non-harvested and non-burned residues, and (ii) the decomposition of soil C, for example through tillage timing and intensity (Ciais et al., 2010). Thus, improved cropland management can greatly increase cropland soil C sequestration (Smith et al., 2008). Specifically, higher crop productivity will lead to increased soil C sequestration (Ciais et al., 2010). Also, reduced tillage, increased cropland irrigation, and increased fertilizer use could increase soil C sequestration. The C sequestration efficiency of croplands can be defined as the ratio of NBP to NPP (Ciais et al., 2010). The C sequestration efficiency of croplands is generally smaller than that for grasslands or forests, reflecting a smaller return of C to the soil in croplands, coupled with an accelerated decomposition of soil organic matter (SOM) due to plowing (e.g., destruction of soil microaggregates and oxygenation).

Live vegetation in croplands generally contains less than 5% of total C, i.e., biomass is a small, transient C pool (Conant et al., 2007). For example, 40-50% of the aboveground biomass in grain crops or all in case of corn for silage are removed during harvest. Thus, soils contain the dominant C pool in croplands. Croplands can be among the most productive ecosystems, are often intensively managed and offer many opportunities to increase the photosynthetic input of C into soil or slow the return of soil C via respiration or fire (Smith et al., 2008). Cropland soils have a high and attainable soil C sequestration potential as they cover about 1,350 Mha globally and may sequester 0.4 to 0.8 Pg C yr^{-1} (Lal, 2004a). Imposing practices that reduce net CO_2 and CH_4 emissions and enhance removals of atmospheric CO_2 and CH_4 will increase stored C, thereby sequestering C or building C sinks. The SOC sequestration in croplands is caused by management practices that add high amounts of biomass to the soil, cause minimal soil disturbance, conserve soil and water, improve soil structure, enhance activity and diversity of soil biota, and strengthen mechanisms of elemental cycling (Lal, 2004a).

Improved agronomic practices that increase yields and generate higher inputs of residue C, in particular, can lead to increased SOC storage (Smith et al., 2008). This may include, for example, (i) using improved crop varieties, (ii) extending crop rotations, notably those with perennial crops which allocate more C below-ground, (iii) avoiding or reducing use of bare (unplanted) fallow, and (iv) adding more nutrients (but the benefits from N fertilizer can be offset by higher emissions of N_2O from soils and CO_2 from fertilizer manufacture). Emissions of CO_2 from crop soils can also be reduced by adopting less intensive cropping systems, which reduce reliance on pesticides and other inputs. For example, the use of rotations with legume crops reduces the reliance on inputs of N. Further agronomic practices are those that provide temporary vegetative cover between agricultural crops as these catch or cover crops add C to soils. The rate of SOC sequestration for cover crops and for diverse cropping systems, for example, has been estimated to be between 50 and 250 kg C ha^{-1} yr^{-1}, respectively (Lal, 2004a).

Other cropland management practices for SOC sequestration are related to nutrient management (Smith et al., 2008). For example, improving the efficiency of crops in using N applied with fertilizers and manure can indirectly reduce emissions of CO_2 from N fertilizer manufacture. Practices that improve N use efficiency include (i) adjusting application rates based on precise estimation of crop needs, (ii) using slow-release fertilizer forms or nitrification inhibitors, (iii) avoiding time delays between N application and plant N uptake, (iv) placing the N more precisely into the soil to make it more accessible to crops roots, (v) avoiding excess N applications, or (vi) eliminating N applications where possible. Integrated nutrient management leading to SOC sequestration includes also applying compost and biosolids. Integrated practices together with manuring have the potential to sequester between 50 and 150 kg C ha^{-1} yr^{-1} in cropland soils (Lal, 2004a).

Adoption of conservation tillage practices has the potential to cause an increase in the SOC storage of croplands. Specifically, many crops can be grown with minimal tillage (reduced tillage) or without tillage (no-till [NT]) (Smith et al., 2008). Since soil disturbance by tillage tends to stimulate soil C losses through enhanced decomposition and erosion, reduced- or no-till agriculture often results in soil C gain, though not always (Baker et al., 2007). Systems that retain crop residues also tend to increase SOC because these residues are the precursors for SOM, the main store of C in the soil. Avoiding the burning of residues, for example, may enhance SOC sequestration. Between 100 and 1,000 kg C ha^{-1} yr^{-1} may be sequestered in cropland soils by adoption of conservation tillage practices (Lal, 2004a).

Globally, 50% of crop production occurs in regions where photosynthesis is co-limited by precipitation, stressing the importance of water availability for crop production (Beer et al., 2010). Thus, expanding the area of cropland under irrigation or using more effective irrigation measures may also enhance C storage in soils through enhanced yields and residue returns (Lal, 2004a). However, some of these gains may be offset by CO_2 from energy used to deliver the water. Further, decreasing excess water availability by drainage of croplands in humid regions may promote NPP and, thus, SOC sequestration (Smith et al., 2008).

Agroforestry is another cropland use with potential for SOC sequestration. It refers to the practice of purposeful growing of trees and crops, and/or animals, in interacting combinations, for a variety of benefits and services (Nair et al., 2008). Numerous and diverse agroforestry systems can be distinguished in tropical and temperate regions (Nair et al., 2009). Agroforestry includes shelter belts and riparian zones/buffer strips with woody species (Smith et al., 2008). Agroforestry systems have a higher potential to sequester atmospheric CO_2 in the SOC pool than the croplands, pastures or natural grasslands they replace (Nair et al., 2009). The incorporation of trees, in particular, is thought to improve soil properties and result in greater net C sequestration (Jandl et al., 2007). The potential for SOC sequestration ranges between 100 and 200 kg C ha^{-1} yr^{-1}, though not always is a C gain observed (Lal 2004a; Peichl et al. 2006). In contrast, enhanced SOC sequestration rates of up to 4.16 Mg ha^{-1} yr^{-1} have also been reported (Beer et al., 1990). Although tropical agroforests may have higher SOC sequestration rates, temperate systems may be more effective in stabilization of the residue C inputs from tree prunings, litter fall and crop residues in the soil (Oelbermann et al., 2006).

Conversion of cropland to NT and reduced tillage practices also yields benefits of placing land use in more sustainable agricultural practice, and reduces emission through diesel consumption used for plowing and other farm operations. When carbon markets become more fully developed, the stored C may be sold as a CO_2 offset, which will earn additional income for the landowners. This Phase II research will lay valuable groundwork for helping to quantify the amount of C stored in soils typical of the MRCSP region.

2.3 United States Croplands and the Regional Carbon Sequestration Partnerships

Croplands in the U.S. occupied about 163 million hectares in 2008, and stored about 14 Pg C in the SOC pool (Conant et al., 2007; EPA, 2010). Further, cropland soils in arid and semiarid climates contained also soil inorganic C (SIC) but its magnitude and dynamic is less well known (Lal and Follett, 2009). However, changes in SIC pools are of minor importance for the cropland C cycle (EPA, 2010).

In 2008, U.S. mineral soils in croplands have been sequestering about 4.9 Tg (1 Tg = 10^{12} g) C, largely through increased production and improved management practices (EPA, 2010).

However, this rate of storage represents a 20% decrease in the rate since 1990 and was largely due to the declining influence of annual cropland enrolled in the Conservation Reserve Program. Cropland is concentrated in the mid-continent region of the U.S. where the highest rates of net C accumulation in mineral soils occurred. For example, Potter et al. (2009) estimated that the Upper Midwest stored about 160 Mg SOC ha^{-1}, a total of 7,283 Tg SOC, and simulated gains of 0.7 Mg SOC ha^{-1} for a 30-yr period. The Midwest region has also the largest amounts of cropland managed with conservation tillage (EPA, 2010). While maintaining or enhancing productivity levels, practices that substantially reduce (reduced-till) or eliminate (no-till) tillage-induced disturbances generally increase soil C pools in croplands. Aside reduced- and no-till, improved crop rotations, yield enhancement measures, organic amendments, cover crops, improved fertilization and irrigation practices, and reduced bare fallow tend to increase productivity and C inputs, and, thus, soil C pools in croplands. In total, the technical potential for annual cropland soil C sequestration in the U.S. has been estimated to be between 50 and 100 Tg C (EPA, 2010). Previously, the SOC sequestration potential of U.S. croplands was estimated at 120 to 270 Tg C yr^{-1} (Lal et al., 1999).

The reduction of CO_2 emissions through C sequestration in U.S. terrestrial ecosystems can be part of the solution to the problem of global warming (Litynski et al., 2006). Thus, to promote CO_2 sequestration in terrestrial ecosystems the U.S. Department of Energy (DOE) created a nationwide network of seven regional partnerships in September 2003. This network represents an area encompassing 96% of the U.S. land mass. Amongst them, the Midwest Regional Carbon Sequestration Partnership (MRCSP) is being led by Battelle Memorial Institute. Originally MRCSP covered the states of Indiana, Kentucky, Maryland, Michigan, Ohio, Pennsylvania, and West Virginia. In 2007, New York joined MRCSP, and New Jersey joined as the ninth member state in 2009. As discussed previously, the region represented by MRCSP contains a large area under cropland with significant potential for terrestrial C sequestration in the soil. During Phase I of the program it was shown that the region represented by the original seven states has substantial resources for sequestering C through improved agricultural and land management practices (Battelle, 2005). The terrestrial sequestration opportunities in this region have the biophysical potential to sequester up to 20% of annual emissions from the region's large point sources of CO_2.

Across the seven states MRCSP region about 4,709 Tg C are stored in SOC in the upper 30 cm of soils, which represents 15% less than the pre-settlement SOC pool (Battelle, 2005). The most potential for terrestrial sequestration in the region exist in non-eroded croplands, eroded croplands, marginal lands under forest, pasture, and severely-eroded croplands, minelands and wetlands. Annually, about 39.3 Tg C of storage capacity is available in these five land use classes. Non-eroded and eroded croplands offer significant terrestrial sequestration potential (3.7 Tg C and 3.1 Tg C per year, respectively). Thus, complete adoption of NT on prime cropping lands would potentially yield an additional 137 Tg of SOC over the next 20 years. Further, ancillary, non-climate benefits associated with the potential large-scale implementation of terrestrial C sequestration within the MRCSP region would be significant and would include improvement in soil quality, reduction in erosion and sedimentation, bio-filtration of pollutants, and decreased rates of CO_2 emissions. Adoption of recommended management practices may enhance crop yield in some soils by 1 to 2% annually, decrease the magnitude of soil erosion and non-point source pollution by 70 to 80%, and reduce the transport of pesticides and heavy metal in runoff and percolation water by 70 to 80%.

Non-eroded prime cropland in the original seven states MRCSP region covered about 10,736 Mha and stored about 688.1 Tg C in the SOC pool to 30-cm depth (Battelle, 2005). In 1992, about 22.5% of the total cropland area was under NT, 17.2% under mulch till, 18.0% under reduced till, and 42.4% under CT. The Phase I Final Report estimated that 3.79 Mha of croplands would be converted to NT from the current area under CT and 1.84 Mha from the current area under mulch till by the year 2012 (Battelle, 2005). The SOC pool to 30-cm depth may increase by 18.8% when converted to NT from CT, and by 14.4% when converted from reduced till to NT. Conversion from CT to reduced till may increase the SOC pool to 30-cm depth by 7.2%. With these assumptions, the average SOC sequestration rate in 30-cm depth was estimated to be 2.79 Tg C annually (Battelle, 2005). Adopting NT on the current CT area, especially for continuous corn and corn-soybean cropping systems, would mainly contribute to this rate of SOC sequestration. In summary, adoption of recommended conservation tillage practices on croplands has a much higher potential for SOC sequestration in croplands of the Midwest region than the national average suggested by the IPCC (Battelle, 2005).

Prime-eroded cropland in the original seven states MRCSP region covered about 1,565 Mha and stored about 61.7 Tg C in the SOC pool to 30-cm depth (Battelle, 2005). Similarly to non-eroded cropland, this SOC pool can potentially be restored by good soil conservation management practices. It has been estimated that conversion from conventional to reduced tillage would sequester 11.0 Tg C and by conversion from conventional to no-till 15.6 Tg C would be sequestered in the SOC pool to 30-cm depth in a 20-year period (Battelle, 2005).

During Phase II (Validation Phase), field tests validated C sequestration practices in respective RCSP regions of the country to enhance terrestrial C storage (Litynski et al., 2008). Among the foci of Phase II of the MRCSP was demonstrating SOC sequestration in cropland soils because their large potential for SOC sequestration was demonstrated during Phase I, and adoption of recommended management practices (RMPs) was identified as a unique opportunity to demonstrate SOC sequestration techniques which can assist in addressing climate change over the long-term (Battelle, 2005).

There is an estimated 10.7 million hectares of prime non-eroded cropland in the MRCSP region. It is estimated that 22.5% or that land area is already practicing NT and will likely remain in that mode. The remaining 77.5% or 8.3 million hectares is potentially amenable to adopting NT or reduced tillage practices, which, if adopted on these lands, would result in an estimated 55 to 74 additional million tons of C sequestered over a 20 year period for the MRCSP region. This is equivalent to 200 to 270 million metric tons of CO_2.

2.4 CMASC Research Facilities & Activities

2.4.1 2006-2010. Research facilities and equipment available include those under ownership of the Carbon Management and Sequestration Center (CMASC) at The Ohio State University. Additional facilities and equipment are available through other laboratories and research centers affiliated with CMASC within The School of Environment and Natural Resources, and The College of Food, Agriculture and Environmental Sciences.

The CMASC research facilities include full laboratory (1300 sq. ft.), greenhouse (500 sq. ft.) and soil sample preparation spaces on the Columbus campus of the Ohio State University. The CMASC also has access to a large number of research farms including Waterman Research Farm, Wooster Ohio Agricultural Research and Development Center (OARDC) Research Facilities, and Coshocton USDA Agricultural Research Station (ARS) Long-term Watershed Monitoring Station among others.

2.4.2 MRCSP Test Locations. Test locations for the MRCSP include the following sites:

- 2006: Thirteen cropland plots over several of the seven states in the MRCSP region, primarily Ohio, Indiana, and Michigan
- 2007: Eleven paired cropland fields across Ohio, Kentucky, and Pennsylvania
- 2008: Five paired cropland fields across Michigan, Ohio, and Pennsylvania
- 2009: Ten paired cropland fields across Michigan, Indiana, and Ohio.

2.4.3 Summary of Operations. Thirteen sites in 2006 from twelve Major Land Resource Areas (MLRA's), 11 sites in 2007 from 11 MLRA's, 5 sites in 2008 from 5 MLRA's, and 10 sites in 2009 from MLRAs of the MRCSP region were selected to collect soil samples from three predominant land uses, namely till, no till and woodlot (Figure 1). Soil samples were collected from five different depths 0-5 cm, 5-10 cm, 10-30 cm, 30-50 cm, and >50 cm in four replications 100 m apart. These samples were analyzed for total soil organic carbon (SOC) and total nitrogen concentrations (N) and various soil physical properties, including soil moisture content, soil bulk density, aggregate size distribution and stability, plant available water, texture, shrinkage, soil compaction, and soil hydraulic properties. A complete range of field and lab studies was conducted to assess the impact of soil C pool on soil quality. Figure 2 shows the Coshocton County field research trial for carbon sequestration under livestock grazing management.

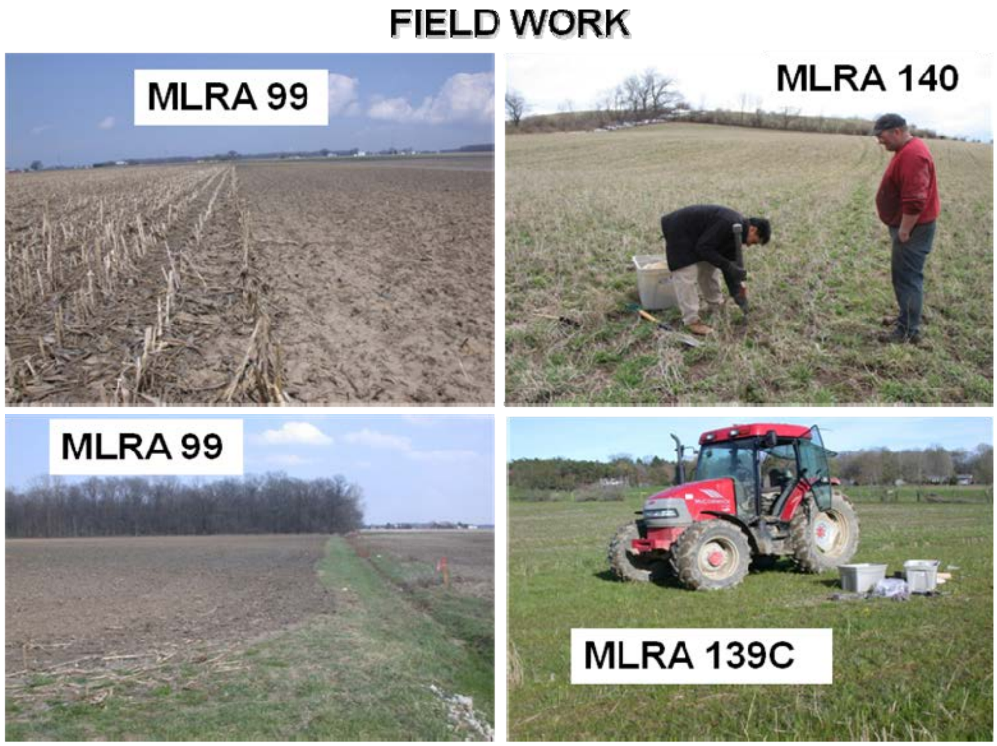

Figure 1. Field work on MLRA Sites

Figure 2. Coshocton County Field Trial for Carbon Sequestration Under Livestock Grazing Management

Three sites based on different parent material: Glacial Till (Coshocton), Till plain (Delaware), and Glacial Lake Plain (Henry county), located in Ohio, were selected to assess the historic carbon loss by cultivation. An additional 144 soil samples and 24 plant residue samples were collected for measuring soil physical properties. Geospatial analysis and pedometrics were conducted with the aim to predict soil C pool in relation to readily available data, such as land use (woodlot, no till, and conventional till), digital elevation model, soil reflectance, and weather data (temperature and precipitation) for the whole MRCSP region.

Figures 3 through 9 show various tools and equipment used in the soil sampling and analysis of soil samples.

Figure 3. The CN Analyzer, for Analyzing Soil Organic Carbon and Total Nitrogen

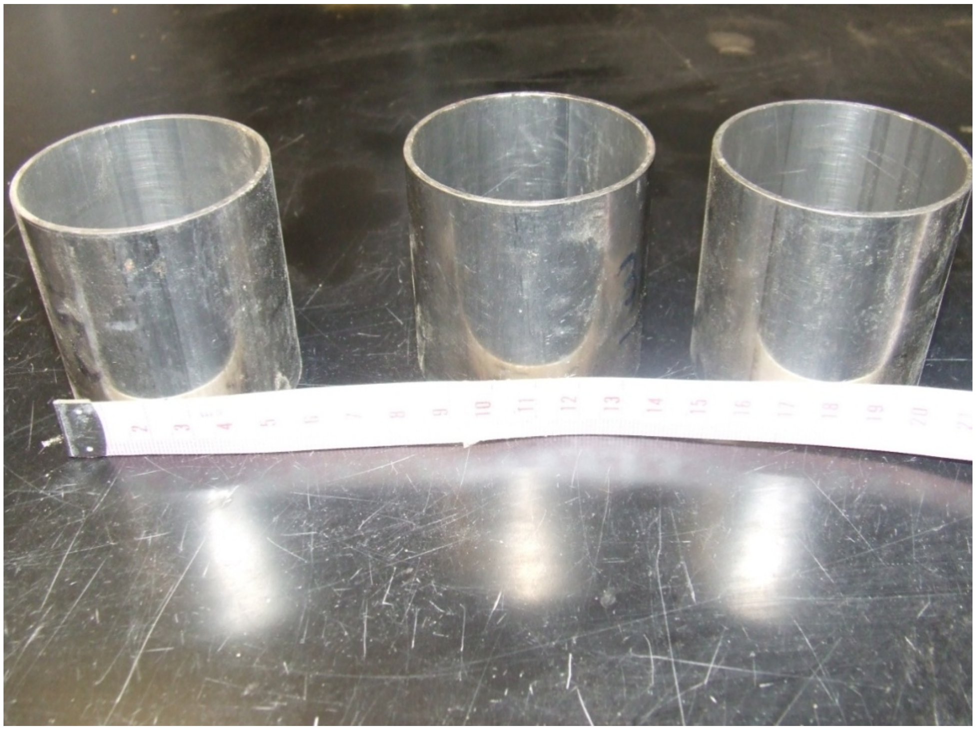

Figure 4. The Soil Cores Used for Measuring Soil Bulk Density

Figure 5. Wet Sieving Apparatus for Analyzing Aggregate Size Distribution, and Stability

Figure 6. Double-Ring Infiltrometer, for Analyzing Soil Water Infiltration Under Field Conditions

Figure 7. Cores for Analyzing Saturated Hydraulic Conductivity in the Laboratory Scale in cm

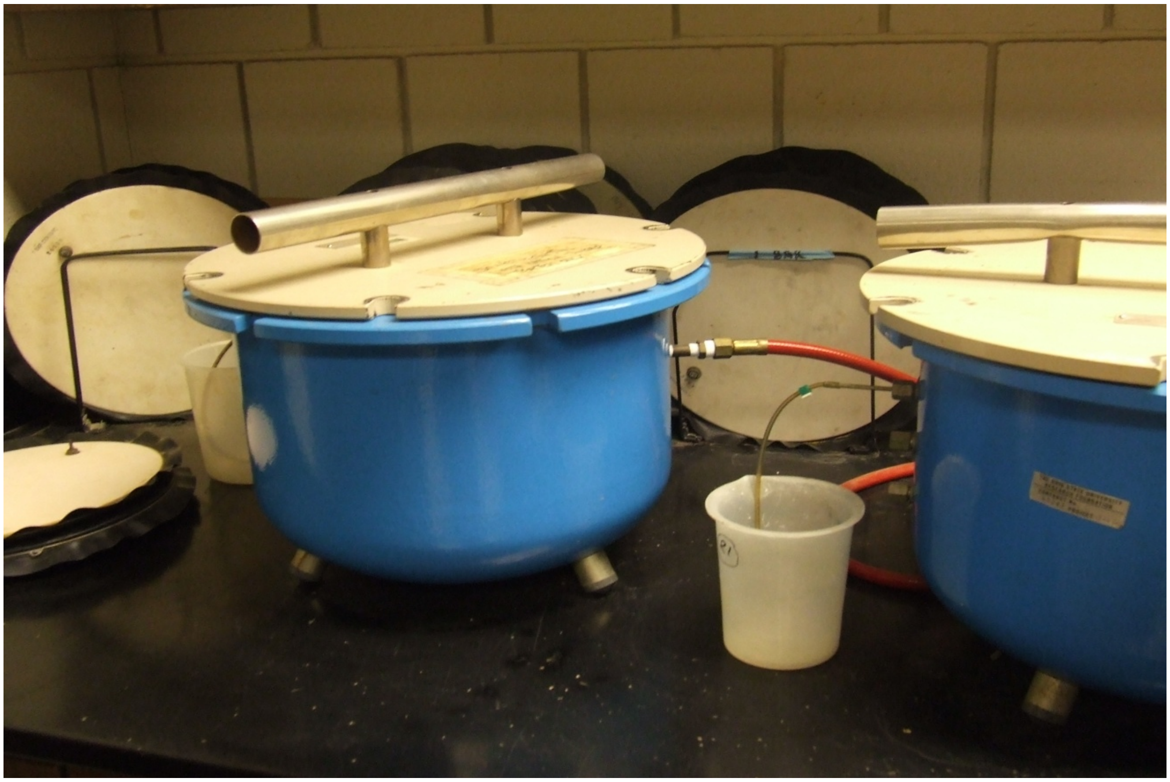

Figure 8. Pressure Chamber for Analyzing Soil Water Retention in the Laboratory

Figure 9. Tools (Shovel, Core Sampler, Gloves and Core) Used for Soil Core Sampling in the Field

2.5 Research Objectives of the MRCSP Field Validation Project

The research work conducted by the CMASC staff and publications that are published as a part of the Midwest Regional Carbon Sequestration Partnership (MRCSP) is discussed in this report. Along with this report, we will describe various methodologies and apparatus, used to analyze different soil characteristics, the soil under field- and lab- conditions. The research objectives were:

- Demonstration of the terrestrial C sink-capacity for predominant land use systems.
- Development of a credible measuring, monitoring, and modeling protocol to evaluate carbon (C) sink capacity in biota and soil at different scales.
- Determination of how C sequestration from MRCSP activities could be incorporated into existing schemes of trading C credits.
- Assessment of mechanisms of C sequestration with regards to land use and soil management.
- Assessment of the soil-profile C distribution to determine C storage within the topsoil and subsoil, and relate it to soil components (particle and aggregate size fractions).
- Evaluation of historic C loss and assess the old vs. new C in soil.
- Establishment of the relationships between soil C and soil physical quality, and agronomic production.

3. PRELIMINARY ASSESSMENT AND SCREENING OF SITES

Soil organic carbon (SOC) is the largest pool in the terrestrial C cycle (>1500 Pg C up to 1.0- m and > 2300 Pg C up to 3.0-m soil depth; Christopher et al., 2009). Globally total soil C pool (2300 Pg) is three times the atmospheric pool (770 Pg) and 3.8 times the biotic pool (610 Pg) (Lal, 2004d). It was reported by Guo et al. (2006) that 23 to 32% of the U.S. soil C is stored in the Midwest region. This stored soil C pool has been disturbed continuously by land use change and ultimately affect other soil properties such as bulk density, pore size distribution, water infiltration etc.

Area under corn cultivation has increased with the increased ethanol production demand in Midwestern region of the U.S.. This could exacerbate the depletion of soil C pool, and also emissions of radiatively-active gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O).This land use change can adversely affect the SOC pool of the Midwestern region, a Corn Belt. Hence, there is a strong need to estimate the SOC pool for this region and implement policies that enhance it to offset anthropogenic emissions. The soil C is spatially variable and, therefore, extensive and accurate soil sampling is required to precisely estimate this C. Soil samples collected at field scale cannot provide the broad picture. Hence, to see the land use effect on different soil properties including soil C, the soils were sampled in different MLRAs. Ideally, the same land use and soil management practice should be sampled at plots established within each MLRA under controlled experimental conditions (i.e., research plots). As field experiments were not available within each MLRA, farmers' fields with different crop rotation, tillage operations, and soil management practices were sampled. Sampling farmer's fields within each MLRA therefore increased the validity of the study results for the entire MRCSP region.

3.1 Criteria for Screening the Sites for Soil Sampling

The criteria for site selection considered factors such as land use type, soil type, sampling scale (field, state or region), slope, cropping history, manure and fertilizer history.

3.1.1 Major Land Resource Areas. Throughout the MRSCP region, the majority of the land use is for corn and soybean. The soil, land use and climate of the region were different in different states; regions with similar soil, climate, physiography are called major land resource areas (MRLAs) (Figure 10). The major soil orders present in the MRCSP region are Alfisols, Entisols, Inceptisols, Mollisols, Histosols, Spodosols. The detailed information about the climate, land use and soil type within different MLRAs are shown in Table 1. The major land uses include forest, grassland, cropland and pasture land. The mean annual temperature ranges from 6.4 to 12.0 °C, and mean annual rainfall ranges from 800-1400 mm. The soil sampling was done in each MLRA to compare the differences.

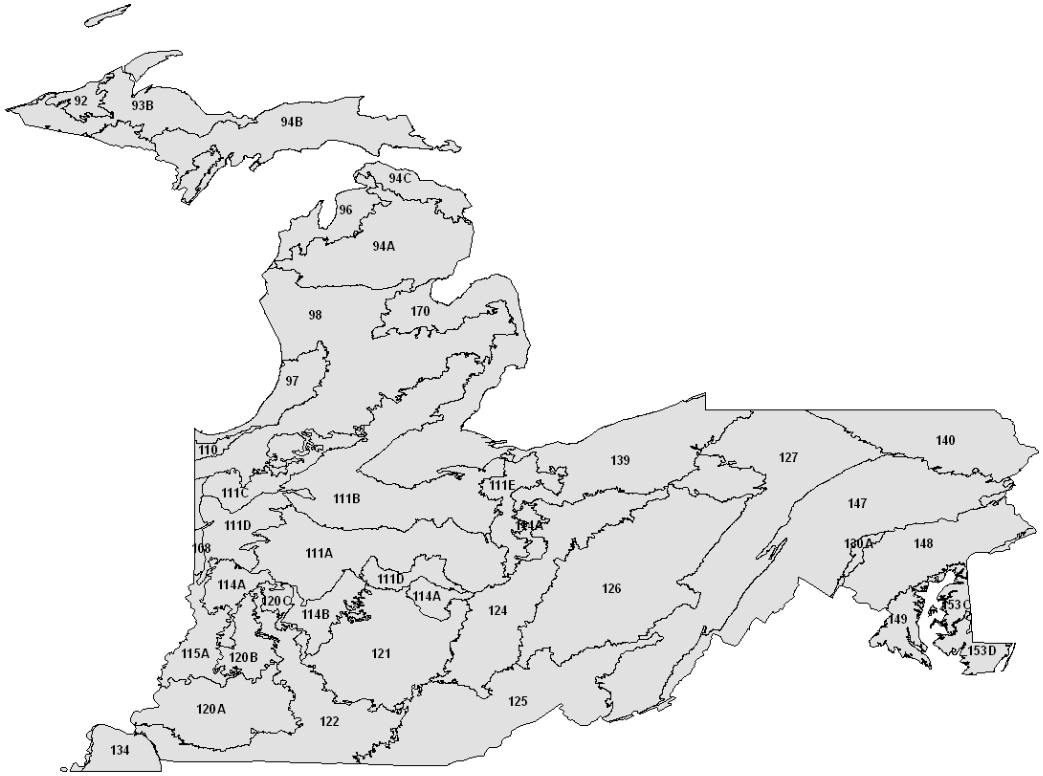

Figure 10. Boundary of the Major Land Resource Areas (MLRAs) of the MRCSP Region Including Seven States

Table 1. The Area, Soil Order, Rainfall, Temperature and Land Use Type in Major Land Resource Areas (MLRAs) Present in Midwestern Region

ID	MLRA	Area	Soil Order	Rainfall (mm)	Temp (°C)	Land use
93B	Superior Stony and Rocky Loamy Plains and Hills, Eastern Part	MI (86%)	Histosols, Spodosols	760-965	3-6	Forest (68%)
92	Superior Lake Plain	MI (39%)	Alfisols, Spodosols	685-940	4-6	Forest (68%), cropland (10%)
96	Western Michigan Fruit Belt	MI	Spodosols, Entisols, Alfisols, and Histosols	760-915	5-9	Forest (54%), cropland (11%), grassland (11%).
97	Southwestern Michigan Fruit and Truck Crop Belt	MI (76%)	Spodosols, Entisols, Alfisols, and Histosols.	890-1,015	8-11	Cropland (34%), Grassland (6%), Forest (21%)
98	Southern Michigan and Northern Indiana Drift Plain	MI (82 %)	Alfisols, Histosols, and Mollisols	735-1,015	7-10	Cropland (47%), Grassland (7%), Forest (23%)
99	Erie-Huron Lake Plain	MI (58%)	Alfisols, Inceptisols, Mollisols, and Spodosols	760-915	7-10	Cropland (59%), Grassland (3%), Forest (12%)

Table 1. The Area, Soil Order, Rainfall, Temperature and Land Use Type in Major Land Resource Areas (MLRAs) Present in Midwestern Region (Continued)

ID	MLRA	Area	Soil Order	Rainfall (mm)	Temp (°C)	Land use
101	Ontario-Erie Plain and Finger Lakes Region	PA (1%)	Alfisols and Inceptisols	735-1,145	5-10	Cropland (36%), Grassland (10%), Forest (31%)
110	Northern Illinois and Indiana Heavy Till Plain	IA (10%)	Alfisols, Histosols, Inceptisols, and Mollisols	785-1,015	7-11	Cropland(65%), Grassland (4%), Forest(5%)
121	Kentucky Bluegrass	KY (83 %)	Alfisols, Inceptisols, and Mollisols	1,040-1,145	10-14	Cropland (22%), Grassland (32%), Forest (28%)
122	Highland Rim and Pennyroyal	KY (43 %), IA (7%)	Alfisols, Inceptisols, and Ultisols	1,090-1,600	11-16	Cropland (23%), Grassland (23%), Forest (40%)
124	Western Allegheny Plateau	OH (53%)	Ultisols and Inceptisols	940-1,145	8-13	Cropland (13%), Grassland (13%)
125	Cumberland Plateau and Mountains	KY (43 %)	Hapludults	940- 1,145	10-15	Forest (73%), Grassland (10%)
126	Central Allegheny Plateau	WV (49%)	Alfisols, Ultisols, and Inceptisols	865-1,145	9-13	Forest(58%), Cropland (12%)
127	Eastern Allegheny Plateau and Mountains	PA (57%)	Ultisols and Inceptisols	840-1,725	6-12	Grassland (6%), Forest (68%)
134	Southern Mississippi Valley Loess	KY (9%)	Alfisols, Entisols, Inceptisols, and Ultisols	1,195-1,525	14-20	Cropland (36%), Grassland(13%), Forest (38%)
139	Lake Erie Glaciated Plateau	OH (62%)	Alfisols	865- 1,270	7-10	Cropland (29%), Grassland (6%), Forest (36%)
140	Glaciated Allegheny Plateau and Catskill Mountains	PA (34%)	Inceptisols	760- 1,145	4-10	Grassland (10%) Forest (60%)
147	Northern Appalachian Ridges and Valleys	PA (54%)	Inceptisols, Ultiso, and Alfisols	785-1,145	7-14	Grassland (11%), Forest (48%)
148	Northern Piedmont	PA (38%)	Alfisols, Inceptisols, and Ultisols	940-1,320	9-14	Forest (25%), Urban development (32%)
108 A	Illinois and Iowa Deep Loess and Drift, Eastern Part	IA (3%)	Mollisols and Alfisols	890- 1,090	8-12	Cropland (80%), Grassland (3%)
111 A	Indiana and Ohio Till Plain, Central Part	central part of Indiana (54%)	Alfisols, Inceptisols, and Mollisols	915 to 1,090	9-12	Cropland (65%), Grassland (6%)
111B	Indiana and Ohio Till Plain, Northeastern Part	northwestern part of Ohio (42%)	Alfisols, Inceptisols, and Mollisols	760- 990	8-11	Cropland (76%), Grassland (3%)
111C	Indiana and Ohio Till Plain, Northwestern Part	Indiana	Alfisols, Mollisols, Entisols, Inceptisols, or Histosols.	890 -990	9-11	Cropland (58%), Grassland (5%)
111 D	Indiana and Ohio Till Plain, Western Part	west-central part of Indiana (73%)	Alfisols, Inceptisols, and Mollisols	915-1,090	10-12	Cropland (74%), Grassland (5%)

Table 1. The Area, Soil Order, Rainfall, Temperature and Land Use Type in Major Land Resource Areas (MLRAs) Present in Midwestern Region (Continued)

ID	**MLRA**	**Area**	**Soil Order**	**Rainfall (mm)**	**Temp (°C)**	**Land use**
111E	Indiana and Ohio Till Plain, Eastern Part	North-central part of OH	Alfisols, Inceptisols, and Mollisols	890-1,040	9-11	Cropland (58%), Forest (18%)
114 A	Southern Illinois and Indiana Thin Loess and Till Plain, Eastern Part	IA (55%)	Alfisols and Inceptisols	940-1,170	9-14	Cropland (61%), Grassland (9%)
114B	Southern Illinois and Indiana Thin Loess and Till Plain, Western Part	IA (34%)	Alfisols and Inceptisols	940-1,170	11-14	Cropland (47%), Grassland (11%)
115 A	Central Mississippi Valley Wooded Slopes, Eastern Part	IA (63%)	Alfisols, Entisols, Inceptisols, and Mollisols	1,015-1,195	11-14	Cropland (69%), Grassland (6%)
120 A	Kentucky and Indiana Sandstone and Shale Hills and Valleys, Southern Part	KY (83 %)	Udalfs	1,145-1,370	13-14	Cropland (36%), Grassland (18%)
120B	Kentucky and Indiana Sandstone and Shale Hills and Valleys, Northwestern Part	IA	Alfisols, Ultisols, and Inceptisols	1,090-1,220	11-13	Cropland (36%), Grassland (18%), Forest (23%)
120C	Kentucky and Indiana Sandstone and Shale Hills and Valleys, Northeastern Part	IA	Alfisols, Ultisols, and Inceptisols	1,040-1,195	11-14	Cropland (29%), Grassland (13%), Forest (35%)
130 A	Northern Blue Ridge	PA (22%), MD (14%), WV (3%)	Dystrudepts, Hapludults, Hapludalfs, or Kanhapludults	915-1,145	9-14	Grassland (17%), Forest (49%)
131 A	Southern Mississippi River Alluvium	KY(1%)	Alfisols, Vertisols, Inceptisols, and Entisols	1,170-1,525	14-21	Cropland (70%), Forest (15%)
144 A	New England and Eastern New York Upland, Southern Part	PA	Entisols, Histosols, and Inceptisols	890-1,145	6-12	Forest (50%), Urban development, (28%)
149 A	Northern Coastal Plain	MD (47%)	Ultisols. Some Entisols, Inceptisols, Spodosols, and Histosols	1,015-1,195	11-14	Forest (25%), Urban development, (32%)
153C	Mid-Atlantic Coastal Plain	MD (62%)	Ultisols, Entisols and Inceptisols	1,015-1,120	12-14	Cropland (40%), Forest (20%)
153 D	Northern Tidewater Area	MD (35%)	Ultisols. Entisols, Histosols, Spodosols, and Inceptisols	965- 1,145	11-15	Forest (31%), Urban development (11%)
90A	Wisconsin and Minnesota Thin Loess and Till, Northern Part	MI(5%)	Alfisols, Entisols, Histosols, and Spodosols	660- 865	3-7	Grassland (7%), Forest (58%)
93B	Superior Stony and Rocky Loamy Plains and Hills, Eastern Part	MI (86%)	Histosols and Spodosols	760- 965	3-6	Forest (68%)
94A	Northern Michigan and Wisconsin Sandy Drift	Lower Peninsula of Michigan	Spodosols, Entisols, Alfisols, and Histosols	685-760	5-9	Grassland (8%), Forest (59%)
94B	Michigan Eastern Upper	Michigan	Alfisols,	760- 915	4-6	Forest (67%)

Table 1. The Area, Soil Order, Rainfall, Temperature and Land Use Type in Major Land Resource Areas (MLRAs) Present in Midwestern Region (Continued)

ID	MLRA	Area	Soil Order	Rainfall (mm)	Temp (°C)	Land use
	Peninsula Sandy Drift	(83%)	Entisols, Histosols, and Spodosols			
94C	Michigan Northern Lower Peninsula Sandy Drift	Lower Peninsula of MI	Spodosols, Alfisols, Entisols, and Histosols	710-865	5-7	Grassland (8%), Forest (71%)
94D	Northern Highland Sandy Drift	MI (1%)	Spodosols and Histosols	760- 890	4-5	Forest (65%)
95A	Northeastern Wisconsin Drift Plain	MI (12%)	Spodosols	760-915	5-8	Cropland (49%), Forest (26%)

3.1.2 Land Use Types. After selecting the MLRAs, different land uses were selected including grassland, forestland, and cropland in the selective MLRA (Table 1). The cropland samples were collected in different tillage systems especially NT and CT. Mostly these tillage practices are long-term ranging from 20-30 years or more. The soil sampling protocol plays a major role while making comparison among different treatments (Christopher at al., 2009). The crop rotations in these tillage practices are generally corn-soybean or corn-corn. The samples were collected in different crop rotations by the CMASC researchers. To evaluate how much soil C is lost or gained while converting from one land use to another. Conversion of conventional tillage to conservation practices (e.g., NT) increases the soil C sequestration. The research showed that the NT practices improve the soil C sequestration compared with CT practices by keeping the crop residues on the ground that can improve the soil C. The CT practices destroy the soil structure, expose the soil organic matter (SOM) and hence decreased the SOC. Hence sampling sites (plots/fields) in the MRCSP region were selected at different locations which were previously conventionally tilled and converted to NT to monitor how much SOC loss/gain occurred after the conversion of NT from CT systems. The past history of the plots where the CT and NT comparison studies performed was known. Both tillage practices were compared in different soil types throughout the region to compare the SOC.

The soil samples were also collected from the forest soils in different MLRAs in order to compare the soil parameters with NT and CT plots. The forest soils are not cultivated and do not contain any crop, hence, these soils are taken as control while making some comparisons with the other tillage treatments or disturbed soils. The soil cores were collected 10-20 cm away from the tree trunk while taking the core samples from the forest soils to avoid disturbance to the tree. The cores were taken generally up to 50 cm depth from these soils.

The NT and CT comparisons cannot be made effectively unless the research conducted at larger scale in different soil types. Hence, more than 20 MLRAs were sampled for comparing different land use systems.

3.1.3 Sampling Depth. It was mentioned previously that the soil C generally increased while conversion from conventional tillage to no tillage. However, it was reported in previous studies that this increase occurs mainly in the surface 0- to 15-cm layer (e.g., Wander et al., 1998). Furthermore, it was reported in the literature that sampling only at shallower depths is underestimating the soil C pool. Hence, to gain a broader understanding of the impacts of different tillage systems and a better estimation of the soil C pool, deeper profile (~1.0 m) sampling across a range soil type, management scenario, and cropping system was performed.

Incorporating the crop residue also improves the SOC. As discusses earlier, the SOC content is increased in CT compared with NT fields in the layer where the residue is incorporated (0-30 cm depth) which is attributed to a greater input of biomass C with depth in CT fields where decomposition may be restricted (Haynes and Beare, 1997; Angers et al., 1997). The lower SOC in deeper NT layers may thus offset the greater SOC in the upper layers, and the total profile SOC between NT and CT soil management may not significantly differ. Thus, the amount of SOC stored in deeper layers (>30 cm) is probably the most important fraction for long-term SOC sequestration. These points should be taken under consideration while sampling. Soil C in conservation tillage where crop residue is incorporated or left over depends on the amount, quality and depth to which the residue is incorporated. The soil sampling depths (in majority of locations) for this study used were 0-10, 10-20, 20-30, 30-40, 40-50, and >50 cm depth.

3.1.4 Sampling Scale. The sampling scale and number of samples needed for making accurate comparisons among different small plots is very important. The field scale sampling generally requires 3-6 replications up to 50 cm depth in each depending on the soil type. The most common sampling design used in the research areas is the complete randomized block design. This design has the least mean sum of squares due to higher degree of freedom of the error as compared to all other designs. However, the randomized block design was used sometimes because of the variations in the soil parameters, and landscape.

The soil sampling at larger scale is very challenging. The soil samples were collected in different MLRAs and from varying land uses within the MLRAs. The geographical information system (GIS) is extensively used these days to estimate the SOC at these larger scalesusing different spatial interpolation methods such as kriging (Scull et al., 2003). Spatial interpolation methods estimate the values of a point source data (soil C in this study) at unsampled locations with GIS modeling (Hengl et al., 2004). These interpolations have been used by different researchers from CMASC to upscale soil C at state and regional scales to obtain satisfactory C predictions. The soils were sampled for validating the model. In addition, the SOC data were also extracted from the National Cooperative Soil Survey (NCSS) database or from soil characterization lab database from different state universities.

3.2 Baseline Field Sampling

The soil core samples were collected prior to any research trial in the field. The initial soil basic properties such as SOC, N, pH, cation exchange capacity (CEC), clay content and bulk density were measured. These data can be used for calculating the SOC pool.

The basic measurements of the soil properties and the method of soil sample collection are provided below.

3.2.1 Soil Chemical Properties. The soil chemical properties such as pH, CEC, total N, SOC, $CaCO_3$, and total P etc. are measured in the lab. The soil cores of 5 by 5 cm or 7.6 by 7.6 cm diameter were used from 0-10, 10-20, 20-30, 30-40, and 40-50 cm depth and collected in the plastic bags and transported to the laboratory and stored in the cooler place until the measurements were taken.

3.2.2 Soil Physical and Hydraulic Properties.

The soil physical and hydraulic properties that were measured during MRCSP projects include: soil bulk density, particle density, K_{sat}, unsaturated hydraulic conductivity, water infiltration, tensile strength, aggregate stability, textural analysis (Appendix B).

Total C, total N and SOC were determined within different locations of varying land uses and were compared among these land uses. These parameters were determined with standard methods. In addition, other soil properties were also measured in order to make better comparisons among different land uses. These other major soil properties were (i) soil bulk density, (ii) saturated hydraulic conductivity, (iii) total N, (iv) aggregate size distribution, (v) carbon associated with different soil fractions, (vi) pH, (vii) water infiltration and (viii) total P. The soil cores and bulk soil samples were obtained in a replicated (usually 3 replications) basis to determine all above mentioned soil properties especially SOC and total N.

The soil samples were usually collected in the summer of every year within different land uses. The disturbed soil samples were collected from different depths as mentioned before and the samples were collected from three sample plots No-tillage (NT), conventional tillage (CT) and forest land (WL). After taking the soil cores from the field, these cores were kept in cooler temperature until samples were analysed.

3.3 Laboratory Analyses and Calculation Methods

The soil samples were analyzed in the laboratory for different soil properties. A few key soil properties and methods used are discussed below.

3.3.1 Water-Stable Aggregates.

Soil samples were collected in natural conditions with shovel from NT, CT and WL areas in three replications from 0-to 10 and 10-to 20 cm soil depth.The aggregate size distribution from this soil was measured using a wet sieving method (Yoder, 1936). The bulk soil samples were passed through 8-and 5-mm mesh to collect soil aggregates between 5-and 8-mm size fractions. A 100-g of aggregates was placed in the first sieve of a nest of sieves with 5-, 2-, 0.5-, and 0.25-mm openings and slowly wetted in tap water for about 20 min. The water level in the container was adjusted so that the base of the top sieve just touched the water and aggregates were allowed to saturate by capillary rise of water. Then the nest was oscillated manually in the water at 60 oscillations min-1 for 2 min. Aggregates retained in the sieves were transferred to beakers using tap water. The weight of each aggregate fraction was recorded after drying at 105°C for 24 h. The data were analyzed to compute WSA (Kemper and Rosenau, 1986), the geometric mean diameter, and the mean weight diameter (Youker and McGuinness, 1956). The SOC and N associated with different aggregate size fractions were also determined by the dry combustion method. To reduce the sample number, aggregates of sizes 0.25 to 0.5 and <0.25 mm were pooled together to cope with the facilities available and time and economic constraints in the determination of the associated SOC concentration. Samples were sealed in the plastic bags and transported to the laboratory.

3.3.2 Soil Bulk Density. The soil cores were trimmed at both ends and bulk density was computed as the weight to volume ratio of oven-dried soils (Grossman and Reinsch, 2002). Soil cores were dried at 105°C until constant weight was obtained (about 48 hours).

3.3.3 Soil C and N. Aggregates were ground and sieved through 0.25-mm sieve for the determination of SOC concentration by the dry combustion method (900°C) using a CN analyzer (Vario Max, Elementar Americas, Hanau, Germany; Nelson and Sommers, 1996). Total N was determined by the Kjeldahl digestion–distillation method (Bremner and Mulvaney, 1982), available P with a modified version of Olsen's method (Olsen and Sommer, 1982), and available K and cation exchange capacity (CEC) by the NH_4OAc method (Thomas, 1982).

Depending upon amount and areal extent, SOC is expressed in Mg C/ha. The SOC and N pool was calculated using Eq. (3).

$$C_{pool}\left({}^{Mg}\!/_{ha} \right) = 10^4 \frac{m^2}{ha} * \left(\frac{d, cm}{100} \right) * \left(\frac{C,\%}{100} \right) * \rho_b \left(\frac{Mg}{m^3} \right) \qquad \text{(Eq 3)}$$

where C_{pool} is the SOC pool (Mg ha^{-1}), ρ_b is the soil bulk density (Mg m^{-3}), and C is the carbon concentrations (%), and d is the soil depth. In case of calculating N pool, the C_{pool} and C% can be replaced with N_{pool} and N (%), respectively, in the Eq.(3).

The C and N concentrations were measured with a CN analyzer using dry combustion method. The soil bulk density was measured by core method and textural properties by the hydrometer and pipette method. When bulk density could not be determined, it was estimated with the textural and SOC data of the soils using pedotransfer functions.

3.3.4 pH. Soil pH was determined with a pH electrode at soil/water ratio of 1:2.5 (w/w).

3.3.5 Textural Analysis. Particle size analysis of surface and sub-surface soil samples (0-0.10 and 0.10-0.20 m) was done using the pipette method (Gee and Or, 2002).

3.3.6 Hydraulic Properties. The saturated hydraulic conductivity was measured with constant head method. The water infiltration was measured in the field using single ring infiltrometer. The soil water retention at different tensions was measured using pressure plate apparatus and using tension table.

4. IMPACTS OF LAND-USE AND MANAGEMENT ON SOIL CARBON

4.1 Impact of No-till on Soil Organic Carbon

> ***“No-till agriculture is one of the optimal management practices that preserves soil and water, and potentially increases soil organic carbon compared with conventional tillage practices.”***

NT agriculture is one of the optimal management practices that conserves soil and water, and potentially increases soil organic C (SOC) compared with conventional tillage (CT) practices. Information on SOC sequestration in NT systems, however, has often been based on measurements for the surface soil (<30 cm) and little is known about the extent of SOC sequestration in NT across the entire soil profile (to 1 m depth). Christopher et al. (2009) conducted a regional study (Figure 11) of NT farming to assess the extent of SOC sequestration in the whole soil profile across 12 contrasting but representative soils of the MRCSP region, each within a MRLA (98, 111C, 114B, 122 in Indiana; 111A, 111B, 111D, 124, and 126 in Ohio; and 127 and 147 in Pennsylvania). Soils on gentle terrain were sampled in paired NT and CT fields as well as in an adjacent woodlot in each MLRA.

The SOC and N concentrations were greater in the surface 0- to 5-cm soil in NT than CT in MLRA 124. The SOC concentration in CT soil was greater than in NT soil for 10 to 30 cm depth in MLRAs 98 and 126. The total SOC pool for the whole soil profile did not differ among NT and CT in eight of the 12 MLRAs and the total profile SOC was actually more under CT in MLRAs 98, 127, and 126, resulting in negative C sequestration rates on conversion from CT to NT in these three MLRAs (Tables 2, 3 and 4). This regional study (Figure 11) suggests that the entire soil profile must be examined when assessing SOC sequestration in NT vs. CT fields (Table 5).

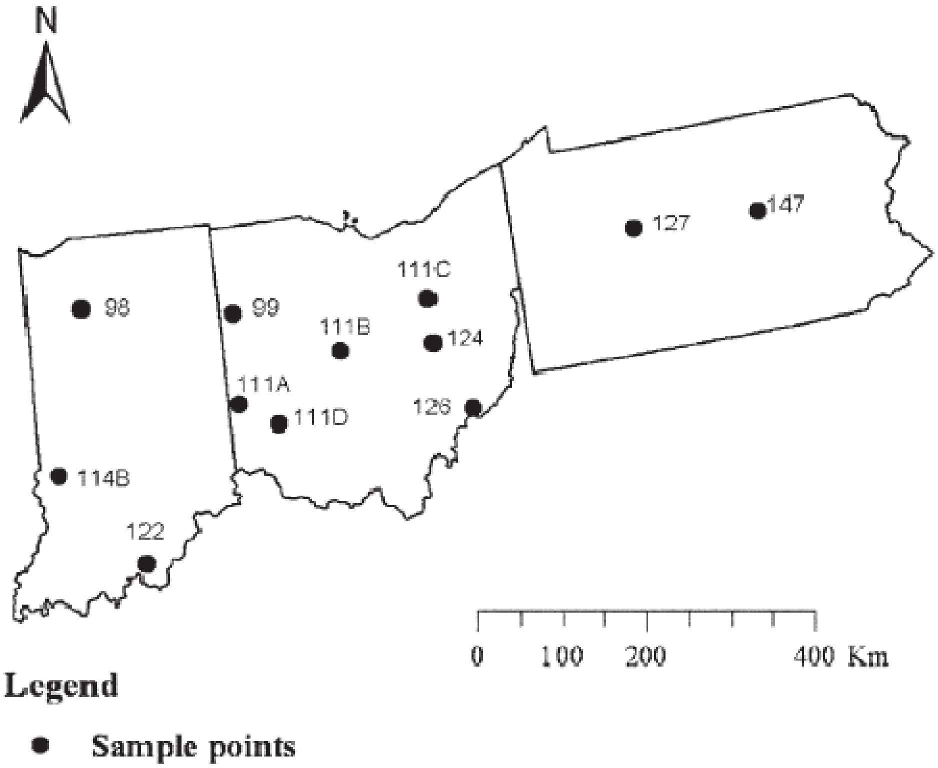

Figure 11. Sampling Sites in the Three States (Indiana, Ohio, and Pennsylvania) Investigated in this Study. Each dot represents sampling locations of no-till, conventional tillage, and woodlot plots in each of the 12 Major Land Resource Areas. (Source: Christopher et al., 2009).

Table 2. The Soil Type, Slope And Management Practices Within the No-Till (NT) and Conventional Till (CT) Sites of Each Major Land Resource Area (MLRA) of Indiana (IN)
(adapted from: Christopher et al., 2009)

MLRA	State	Management	Soil Series	Slope (%)
98	IN	30-yr NT corn-soybean rotation receiving 134 kg ha^{-1} N, 9 kg ha^{-1} P, and 280 kg ha^{-1} K for corn; 30-yr CT rotation of 2 yr corn and 1 yr soybean receiving 50 kg ha^{-1} N and side-dressed with NH_3, 44 kg ha^{-1} P, and 93 kg ha^{-1} K for corn, and 118 kg ha^{-1} K for soybean.	Maumee loamy sand	1
111C	IN	10-yr NT and CT under 3-yr soybean and 2-yr corn rotation	Martinsville silt loam	<2
114B	IN	23-yr NT and CT under corn-soybean receiving 180 kg ha^{-1} of anhydrous NH_3 for corn	Iva silt loam	3
122	IN	10-yr NT corn-soybean rotation and 10-yr CT corn-wheat-soybean-soybean rotation	Crider silt loam	2

Table 3. The Soil Type, Slope And Management Practices Within The No-Till (NT) and Conventional Till (CT) Sites of Each Major Land Resource Area (MLRA) of Pennsylvania (PA)
(adapted from: Christopher et al., 2009)

MLRA	State	Management	Soil Series	Slope (%)
127	PA	8-yr NT in 4-yr corn-alfalfa rotation receiving 33.3 m^3 liquid manure for corn; 8-yr CT in corn-alfalfa-nurse crop every 4-yr receiving 46.7 m^3 liquid manure for corn	Gilpin silt loam	4
147	PA	9-yr NT corn-soybean rotation receiving 74.5 m^3 of dairy manure; 9-yr CT corn-soybean rotation receiving 30 kg ha^{-1} N, 29 kg ha^{-1} P, and 56 kg ha^{-1} K	Edomsilty clay loam	5

Table 4. The soil Type, Slope and Management Practices Within the No-Till (NT) and Conventional Till (CT) Sites of Each Major Land Resource Area (MLRA) of Ohio (OH)

(adapted from: Christopher et al., 2009)

MLRA	State	Management	Soil Series	Slope (%)
99	OH	5-yr NT and CT corn-soybean-wheat rotation receiving 20 kg ha^{-1} N, 23 kg ha^{-1} P, 7 kg ha^{-1} K, 188 kg ha^{-1} magnesium, and 5 kg ha^{-1} Zn and S	Hoytville clay	<1
111A	OH	18-yr NT and CT corn-soybean rotation receiving 76 kg ha^{-1} N, 333 kg ha^{-1} P, and 186 kg ha^{-1} K every other year	Kokomo silty clay loam/Celina silt loam	1-2
111B	OH	20-yr NT and CT corn-soybean rotation with occasional wheat receiving 101 kg ha^{-1} N for corn and 57 kg ha^{-1} K for soybean	Milton silt loam/Glynwood silt loam	1
111D	OH	5-yr NT and CT corn-soybean rotation with 94 Mg ha^{-1} municipal sewage wastewater containing 44 kg ha^{-1} N	Xenia/Fincastle	1
124	OH	35-yr NT rotation of 2-yr corn and 5-6-yr alfalfa; 35-yr CT continuous corn, both fields receiving 202 kg ha^{-1} N, 157 kg ha^{-1} P, and 168 kg ha^{-1} for corn	Allegheny silt loam	5
126	OH	15-yr NT corn-soybean-rye (cover crop) rotation receiving 29.9 m^3 of liquid manure; 15-yr CT corn-soybean rotation with 29.9 m^3 of liquid manure	Otwell silt loam/Melvin silt loam	2-6

Table 5. The Soil Organic Carbon (SOC) Within Different Land Uses of Major Land Resource Area of Indiana, Ohio, and Pennsylvania
(adapted from: Christopher et al. (2009)

Depth	Land use	Soil Organic C											
		Indiana				**Ohio**						**Pennsylvania**	
		98	**111C**	**114B**	**122**	**99**	**111A**	**111B**	**111D**	**124**	**126**	**127**	**146**
cm		g kg^{-1}											
0-5	CT	30.0	16.8	16.2	11.5	20.4	16.9	16.9	19.3	11.3	25.9	28.2	22.0
	NT	17.2	22.9	11.1	12.9	23.5	15.3	15.3	17.9	21.6	22.2	24.3	24.5
	W	51.8	46.1	21.1	33.6	76.0	23.5	23.5	41.0	29.6	32.3	42.0	66.4
5-10	CT	29.9	17.1	9.3	9.8	20.1	10.4	10.4	19.3	11.3	24.6	26.6	19.9
	NT	10.8	18.7	7.8	9.2	21.8	11.0	11.0	15.9	13.4	16.4	20.9	26.8
	W	24.9	29.9	11.6	16.4	62.6	19.2	19.2	26.8	18.5	16.9	30.7	31.7
10-30	CT	28.1	15.8	6.5	7.9	17.7	9.1	9.1	16.4	11.1	19.4	26.8	19.9
	NT	12.5	18.2	7.1	7.9	18.5	7.9	7.9	10.9	9.0	11.0	20.8	13.7
	W	23.2	42.4	11.3	9.5	54.5	22.4	22.4	19.9	10.0	13.2	28.9	16.9
30-50	CT	5.4	7.1	3.8	4.5	17.7	5.4	5.4	9.4	7.0	10.5	15.8	6.4
	NT	3.1	7.9	3.8	4.5	8.0	5.1	5.1	6.6	5.0	3.2	6.5	3.2
	W	3.6	18.9	6.3	5.2	54.5	7.5	7.5	11.4	5.2	3.8	7.9	8.3
50-60	CT	5.4	4.7	2.9	4.0	5.8	5.6	5.6	5.5	4.8	6.5	29.7	2.1
	NT	1.7	7.7	2.4	2.8	6.1	4.0	4.0	4.8	3.0	2.0	6.3	2.0
	W	3.0	9.3	5.0	4.5	ND	6.1	6.1	8.7	3.2	2.5	9.8	5.6
LSD for interaction ($P>0.05$)		9.4	9.2	2.3	5.4	8.6	5.9	N/A	7.3	5.2	4.2	6.3	14.0

In a complementary study, Christopher and Lal (2007) examined the management practices which contribute to maximizing N availability for optimizing sequestration of atmospheric CO_2 into soil humus. They reported that farming practices which enhance nutrient use, reduce or eliminate tillage, and increase crop intensity, together, affect N availability and, therefore, C sequestration (Figure 12, Table 6).

Table 6. Rate of Soil Organic C (SOC) Gain or Loss Since Conversion from Conventional Tillage (CT) to No Till (NT) Farming. Comparisons were made in each Major Land Resource Area (MLRA) in the 0- to 30- and 0- to 60-cm soil layers (adapted from: Christopher et al., 2009).

Duration of NT (year)	MLRA	SOC gain or loss (Mg ha^{-1} $year^{-1}$) in NT vs. CT fields 0-30 cm	0-60 cm
30	98	-1.3	-1.2
10	111C	0.8	1.1
23	114B	-0.2	-0.2
10	122	-0.1	-0.2
5	99	1.1	1.4
18	111A	0.7	1.0
20	111B	-0.1	-0.1
5	111D	-1.1	-1.3
35	124	0.2	0.2
15	126	-1.0	-1.5
8	127	-1.6	-11.0
9	147	0.5	0.0

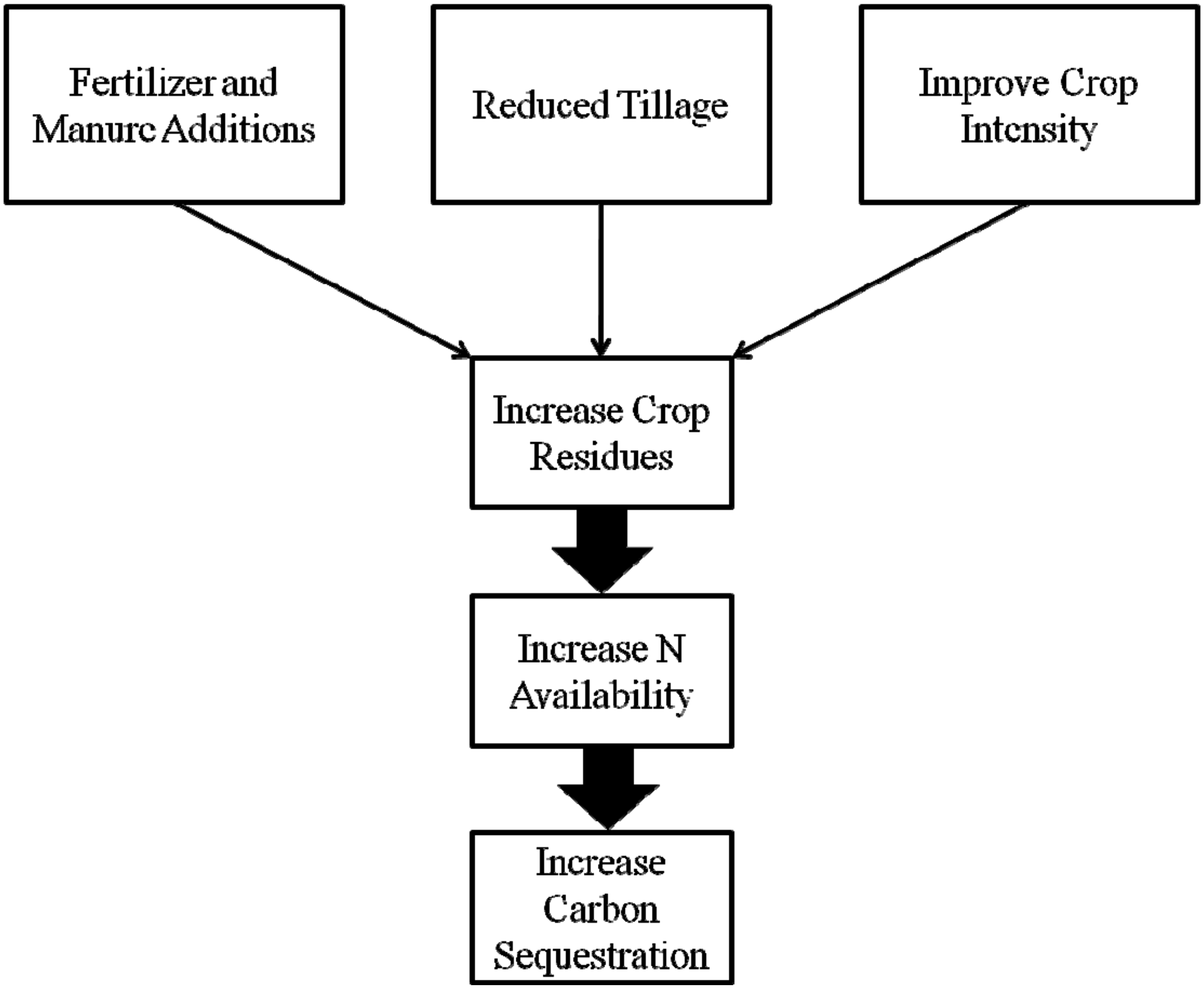

Figure 12. Optimum Management Practices that Enhance N Availability and Carbon Sequestration (Source: Christopher and Lal, 2007)

Christopher and Lal (2007) concluded that:

- N additions, especially from livestock manure and leguminous cover crops, are necessary for increasing grain and biomass yields and returning crop residues to the soil thereby increasing SOC concentration;
- Conservation tillage practices enhance also the availability of N and increase SOC concentration;
- Increase in cropping intensity and/or crop rotations produce higher quantity and quality of residues, increase availability of N, and therefore foster increase in C sequestration; and
- The benefits of C sequestration from N additions may be negated by CO and N_2O emissions associated with production and application of N fertilizers.

Chatterjee and Lal (2009) evaluated the impact of long-term (>4 yr) NT-based cropping systems on SOC sequestration and selected soil physical and chemical parameters across soils within five MRLAs (99 and 111 in Michigan; 124 and 139 in Ohio; and 127 in Pennsylvania) in the MRCSP region (Table 7). Soil samples were collected from paired fields of NT and plow tillage (PT) based cropping systems and an adjacent woodlot (WL). The SOC concentration, bulk density (ρ_b), texture, pH, electrical conductivity (EC), soil N, coarse particulate organic matter (CPOM) C and N, and nitrate N (NO_3-N) concentrations were determined.

Chatterjee and Lal (2009) reported that NT soils had higher SOC concentration in soils by 30, 50 and 67% over PT soils for 0–5 cm depth in MLRAs 99, 111 and 127, respectively, (Table 8). Considering the whole soil profile SOC, WL had higher SOC pool than NT and PT practices in MLRAs 99, 111 and 124. However, there was no significant difference ($P < 0.05$) between NT and PT practices across five soils (Table 8). Almost the same trend was observed in the case of depth-wise soil N content. The NT soil had higher N content than PT soils by 27, 44 and 54% under MLRAs 99, 127 and 111, respectively. However, whole soil profile N content of NT soil was significantly higher by 12% than PT soil in MLRA 99. Concentrations of CPOM associated C and N of NT soil was higher than PT soil under MLRAs 99, 111 and 127 at 0–5 soil depth (Tables 9, 10).

Table 7. The Location, Soil, Slope and Management Information Practices of Paired NT and Tilled Fields in Three Different States (adapted from: Chatterjee and Lal, 2009)

MLRA	Site location	Soil series	Slope	Taxonomic classification	Management
Michigan					
99	Temperence	Pewamo clay loam	0-1%	Fine, mixed, active, mesic typic Agriaquolls	10-yr corn-soybean-wheat rotation, wheat: receiving 100L of liquid fertilizer containing 5% N, 14% P, and 4% K and 50 L side dressed of the same mixture and corn receiving 200L of 28% N liquid fertilizer and 55 kg K, PT field receiving 55 kg K ha^{-1}
111	Lenawee	Hoytville clay loam and silty clay loam	0-3%	Fine, illitic, mesic, mollicepiaqualfs	10-yr corn-soybean-wheat, wheat receiving 10 kg N ha^{-1} and 50 L of liquid fertilizer containing 10% N, 34% P and PT: corn-soybean receiving 60 kg N ha^{-1}
Ohio					
124	Scioto	Genesee	0-2%	Fine-loamy, mixed, superactive, mesic, fluventicEutrudepts	15-yr corn-soybean receiving 30 kg N, 76 kg P, and 100 kg K ha^{-1} every 2 yr
139	Canal Fulton	Chili silt loam	2-6%	Fine-loamy, mixed, active, mesic typic Hapludalfs	6-yr corn-soybean and PT, 2 yr corn before that alfalfa, NT com receiving 190 L of liquid fertilizer containing 28% N and for PT corn receiving 185 L of liquid fertilizer mixture containing 10% N, 34% P, and current year 65 kg N and 75 kg K ha^{-1} was applied
Pennsylvania					
127	Salisbury	Cookport loam	3-8%	Fine-loamy, mixed, active, mesicaquicFragiudults	30-yr alfalfa receiving 113 kg N ha^{-1} and 54 m^3 of liquid manure; PT com receiving 284 kg N ha^{-1}

Table 8. The Soil Organic Carbon (g kg^{-1}) for No Tillage (NT), Plow Tillage (PT), and Woodlot (WL) for Different Major Land Resource Areas (MLRA) (adapted from: Chatterjee and Lal, 2009)

		Soil Depth (cm)				
MLRA	**Treatments**	**0-5**	**5-10**	**10-30**	**30-50**	**50-60**
99	NT	30.7	23.4	19.7	8.10	6.30
	PT	23.7	23.6	22.7	14.1	8.80
	WL	66.0	56.4	32.6	10.1	6.90
	LSD (0.05)	3.10	9.30	10.3	6.40	4.90
111	NT	29.3	20.3	14.0	6.70	5.40
	PT	19.5	20.0	17.3	8.60	4.00
	WL	51.2	32.5	24.9	11.9	8.50
	LSD (0.05)	2.10	5.50	7.10	7.10	4.60
124	NT	21.7	17.5	16.2	15.3	17.3
	PT	26.6	22.0	22.7	18.9	19.5
	WL	72.5	58.8	38.0	32.0	31.3
	LSD (0.05)	26.4	39.4	11.2	10.0	16.8
139	NT	15.8	11.4	8.90	3.90	2.80
	PT	18.9	19.3	11.3	9.40	7.50
	WL	21.3	14.5	10.5	9.80	4.20
	LSD (0.05)	4.10	5.00	8.50	8.70	3.50
127	NT	36.5	23.1	15.6	9.70	8.80
	PT	21.8	19.9	17.5	8.60	6.40
	WL	30.2	22.4	18.0	13.8	7.10
	LSD (0.05)	10.5	4.10	4.60	6.00	4.00

Table 9. The Total Soil Nitrogen (g kg^{-1}) for No Tillage (NT), Plow Tillage (PT), and Woodlot (WL) for Different Major Land Resource Areas (MLRA) (adapted from: Chatterjee and Lal, 2009)

		Soil Depths					
MLRA	**Treatments**	**0-5**	**5-10**	**10-30**	**30-50**	**50-60**	**Total**
99	NT	1.92	1.64	3.17	1.36	1.33	10.5
	PT	1.51	1.51	3.30	2.35	1.78	9.42
	WL	2.30	2.55	4.25	1.82	1.39	12.3
	LSD (0.05)	0.16	0.67	0.59	0.69	0.92	0.85
111	NT	2.28	1.67	2.74	1.52	1.60	9.18
	PT	1.48	1.61	2.95	1.97	1.17	9.80
	WL	2.62	2.10	3.29	1.94	2.04	12.0
	LSD (0.05)	0.31	0.31	0.89	0.89	1.29	2.55
124	NT	0.99	1.65	2.87	2.71	1.73	12.5
	PT	0.97	1.98	4.09	3.07	2.39	9.94
	WL	0.71	1.58	3.91	3.35	3.26	12.8
	LSD (0.05)	0.37	1.15	1.94	1.45	1.71	3.42
139	NT	1.15	0.89	1.31	0.84	0.82	6.32
	PT	1.30	1.22	1.57	1.21	1.01	5.01
	WL	1.34	1.10	1.52	1.33	1.49	6.78
	LSD (0.05)	0.30	0.42	1.00	0.78	0.87	2.83
127	NT	2.29	1.70	2.44	1.53	1.53	8.46
	PT	1.59	1.47	2.34	1.69	1.37	9.50
	WL	1.75	1.79	2.54	2.19	1.33	9.60
	LSD (0.05)	0.67	0.49	0.73	1.07	0.67	1.71

Table 10. Mean Coarse Particulate Organic Matter Associated Carbon (CPOM-C) and Nitrogen (CPOM-N) Concentrations for Woodlot (WL), No-Tillage (NT), and Plow Tillage (PT) in Different Major Land Resource Areas (MLRA) (adapted from: Chatterjee and Lal, 2009).

		CPOM-C		CPOM-N	
MLRA	**Treatments**	**0-5**	**5-10**	**0-5**	**5-10**
99	NT	92.4	46.8	5.88	3.43
	PT	47.7	40.0	2.86	2.55
	WL	202	139	12.6	9.61
	LSD (0.05)	27.6	47.8	1.93	3.82
111	NT	79.3	31.6	6.05	2.71
	PT	33.0	32.4	2.19	2.21
	WL	128	60.9	8.81	4.61
	LSD (0.05)	36.1	16.4	2.19	1.42
124	NT	40.7	20.4	2.90	1.54
	PT	58.0	26.5	4.24	1.82
	WL	440	185	30.6	11.1
	LSD (0.05)	319	194	24.8	14.3
139	NT	37.8	15.7	2.67	0.99
	PT	51.3	45.3	3.45	3.28
	WL	63.7	39.1	4.03	1.74
	LSD (0.05)	19.5	32.9	1.43	1.38
127	NT	123	52.7	9.77	3.64
	PT	68.2	63.9	4.57	4.22
	WL	75.4	40.9	4.95	2.92
	LSD (0.05)	50.2	35.9	3.63	2.26

Other studies by the MRCSP team at OSU have shown that additional benefits of NT over CT in soil C sequestration may be negligible if the entire soil profile is considered because of the fact that CT adds an SOC pool at the bottom of the plough layer compared to an addition of SOC in the upper 20-cm by NT practices (Blanco-Canqui and Lal, 2008; Christopher et al., 2009; Mishra et al., 2010b). However, NT provides other benefits such as improving diversity in soil biota and soil structure, reducing soil erosion and sedimentation of water bodies, and reducing the overall consumption of fossil fuel and CO_2 emission from agricultural fields. Future soil C sequestration and other C offset programs require the development of optimum land use change scenarios for maximizing terrestrial C sequestration while maintaining environmental sustainability. Complete LCA is needed to assess the ecosystem C budget.

The results discussed in this Chapter indicate that impact of tillage on soil C and associated soil quality parameters is confined within specific soil types, and cannot be generalized for the entire MRCSP region. Information on published papers resulting from these studies is presented in Appendix C.

5. CROP RESIDUE MANAGEMENT INFLUENCES ON SOIL PROPERTIES

Management of crop residues is vital for sustainable land management. Studies by MRCSP have consistently shown that large improvements are made with regard to C sequestration, mitigating soil erosion, and improving soil quality and tilth when management strategies are employed that conserve and leave in place crop residues such as no-till and conservation tillage practices. The MRCSP team has established several long-term, large-scale research plots at on various research facilities and farms across the state of Ohio and within the 7-state covering the entire MRCSP region.

In 2007, a long-term research trial on soil structure and carbon interactions within soils was completed on a research trial in central Ohio. Papers resulting from this research are listed in Appendix C. Blanco-Canqui and Lal (2007a) reported that retention of wheat straw in no-till (NT) practices increased aggregate tensile strength, increased SOC, and retained higher moisture levels. The annual rate of C sequestration was 1.2 Mg ha^{-1}, with the mean of wheat straw converted into SOC being pool ~ 33%. These data strongly suggest that long-term straw mulching increased SOC concentration, improved near-surface aggregation, and improved crop yields. Figures 13 and 14 show the different tillage management in clay soils of Ohio.

Figure 13. Drying and Cracking of Soil Under Conventional Tillage Management in Hoytville, Ohio, from Which Residue is Removed

Figure 14. Soil Landscape in Hoytville, Ohio. The Lake-Derived Soils are Flat, Poorly Drained, and High in Clay Content.

Figure 15 shows the soil sampled collected from the research trials in Ohio for analyzing soil stability analysis (Blanco-Canqui and Lal, 2007a).

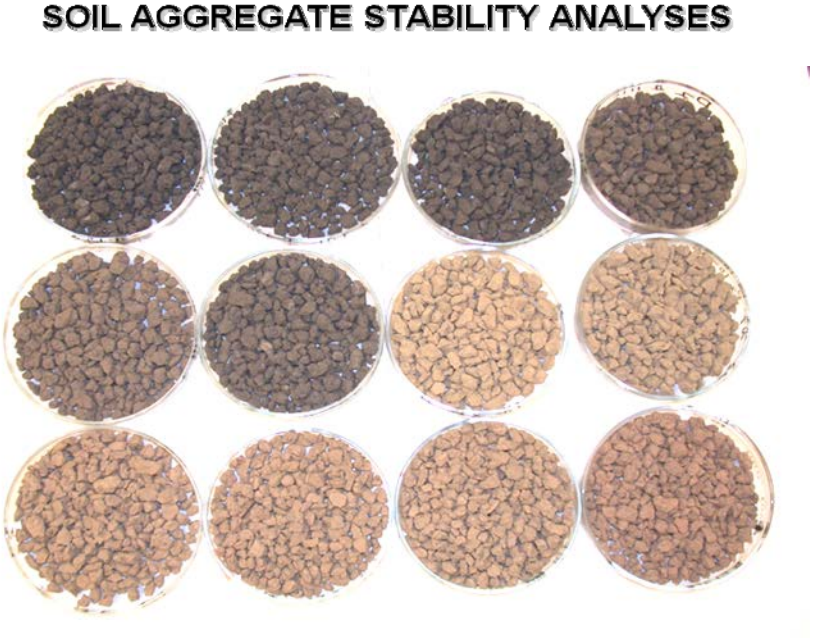

Figure 15. Samples Collected from MRCSP Farms

SOC concentrations are highly correlated with physical properties of soils (Figures 16, 17, 18, 19) which, in part, determine overall soil quality and agronomic productivity potential. This reemphasizes the importance of management practices on SOC. The data strongly corroborated evidence that leaving crop residue on the surface of the soils is critical to improving soil quality and sequestering C (Blanco-Canqui and Lal, 2007a).

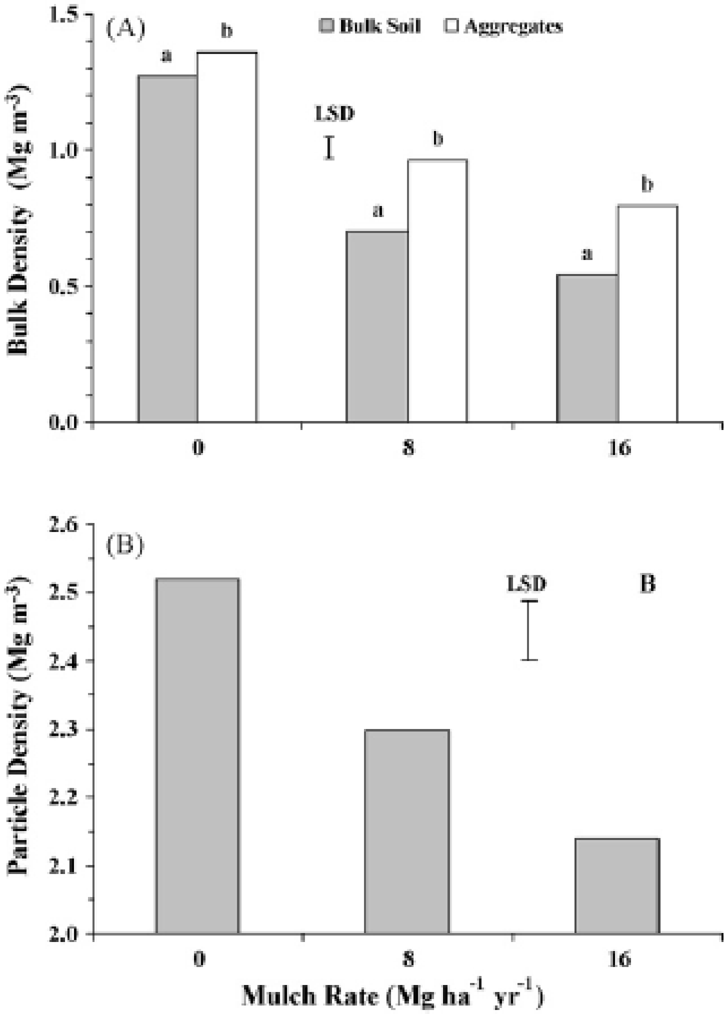

Figure 16. Bulk Density and Particle Size Density Under No-Till Straw Mulching System Source: Blanco-Canqui and Lal (2007a)

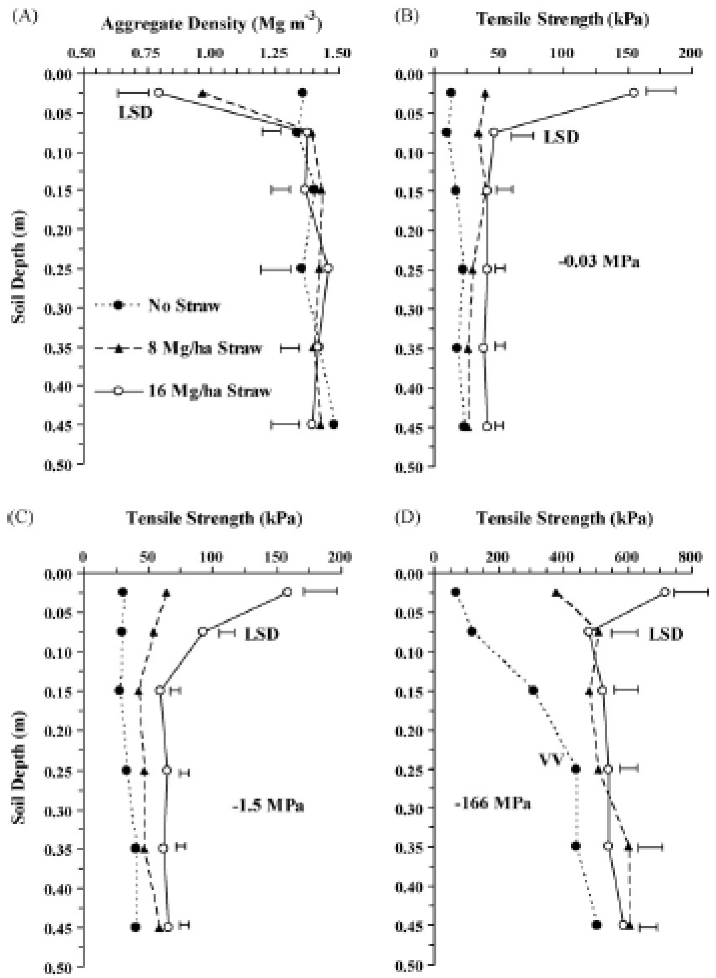

Figure 17. Aggregate Density and Tensile Strength Under No-Till Straw Mulching System
Source: Blanco-Canqui and Lal (2007a)

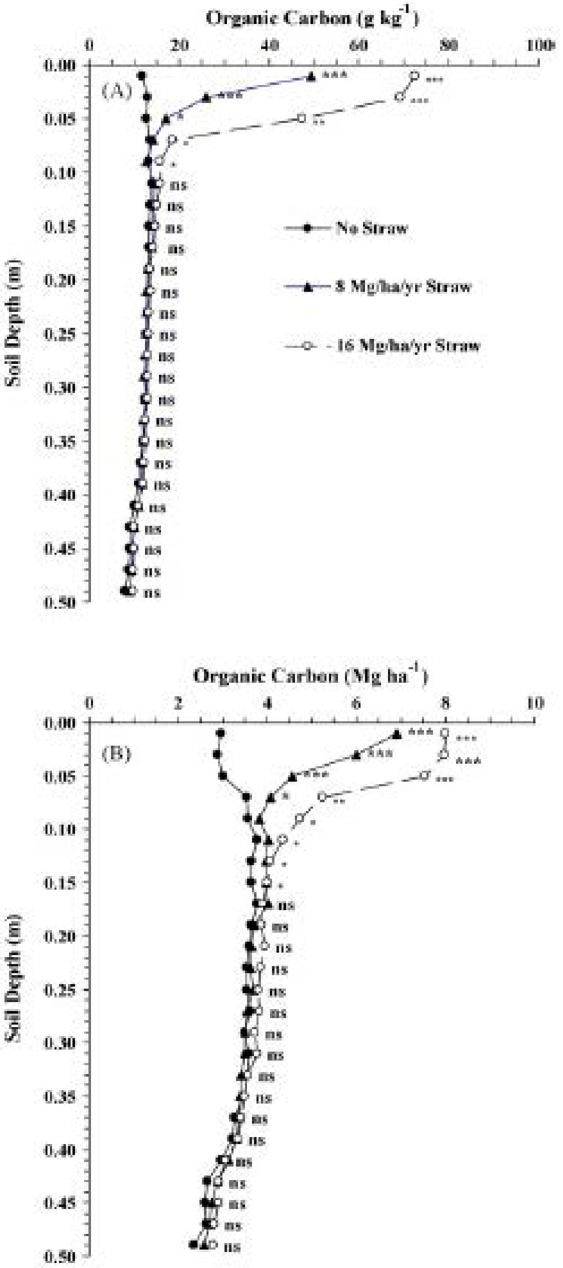

Figure 18. Depth Distribution of Soil Organic Carbon (Mg ha⁻¹) for Three Treatments: no Straw, 8 Mg ha⁻¹, and 16 Mg ha⁻¹ (Source: Blanco-Canqui and Lal, 2007a).

In addition to improving the carbon content of the soil, crop residues are also useful for the biofuel production as an alternative to conventional fuels (Pacala and Socolow, 2004). Depending on quality and quantity, crop residue significantly affects the properties of the soil. It protects the soil surface from raindrop impact, reduces evaporation, increases SOM content, recycles nutrients, and improves the overall soil structure and quality (Blanco-Canqui and Lal, 2007a). However, intensive removal of corn stover as biofuel may negatively affect soil hydraulic properties.

Left over stover on the soil surface provides food source and habitat to the micro-organisms (earthworms) which are responsible for the development of macropore network (Blanco and Lal, 2007b).

A study conducted by Blanco-Canqui and Lal (2007b) reported the drawbacks of removal of the corn stover from the NT plots indicating following.

(1) Removal of corn stover seals the open and continuous macropores which can be a major factor in reducing near surface parameters of water flow and gaseous diffusion and transport such as K_{sat} and air permeability (Ela et al., 1992; Loll et al., 1999).

(2) Corn stover removal may affect soil properties as it is coarser, less decomposable, and thus remains longer on the soil surface (Mankin et al., 1996).

(3) Corn stover build up the soil C and improve the soil properties by increasing porosity, water percolation, hydraulic conductivity and water retention in the soils.

6. CROP RESIDUE REMOVAL FOR BIOENERGY

Increasing global demand for energy has created a large and growing market for bioenergy products. Reducing anthropogenic C emissions is necessary for mitigating climate change. Thus, developing C-neutral and C-negative renewable energy sources is necessary for replacing fossil fuels.

Crop residues have been proposed as a potential source of biomass for renewable energy generation as the machinery, equipment and storage facilities for these residual materials are often already available on farms and capital expenditures are far less than for crops purposely grown for bioenergy since crop residues are already available within current agronomic systems. Lal (2004d) has estimated crop residues in the U.S. to be 367×10^6 Mg/year for 9 cereal crops, 450×10^6 Mg/year for cereals and legumes, and 488 $x10^6$ Mg/year for 21 crops. Globally, Lal (2004d) estimates 2802×10^6 Mg/year for cereal crops, 3107×10^6 Mg/year for 17 cereals and legumes, and 3758×10^6 for 27 food crops. Thus, there is a significant annual productivity of crop residues estimated at nearly 1 billion barrels (bbl) of diesel equivalent for the US and 7.5 bbl of diesel equivalent globally.

However, use of crop residues is not without costs (Lal and Pimentel, 2007). While renewable bioenergy is likely to be necessary, a careful and objective analysis of impacts on SOC sequestration, agronomic productivity, and environmental sustainability is warranted.

In the U.S. and particularly within the MRCSP region, corn (*Zea mays* L.) stover has been proposed as a primary bioenergy feedstock for biomass energy and biofuel production due to ubiquity of corn as a staple crop for the region. However, such an appropriation should be done with a full lifecycle analysis and impact assessment on soil quality and agronomic productivity.

The MRCSP conducted a 2½ year study of stover removal on no-till and conventional tillage continuous corn management on three different soils representative of a large percentage of soils in the U.S. Midwest (Figures 19 and 20). Corn stover was removed at five rates: 0, 25, 50, 75, and 100%. While SOC and soil productivity was highly dependent on soil type, drainage and topography, the data clearly indicated detrimental impacts at >25% stover removal. Greater than 25% stover removal lead to reduced SOC, reduced profile water availability, decreased earthworm population, increased soil strength, and decrease in crop yields (Figures 21, 22; Blanco-Canqui et al., 2006c). Information on published papers describing this study is presented in the Appendix C.

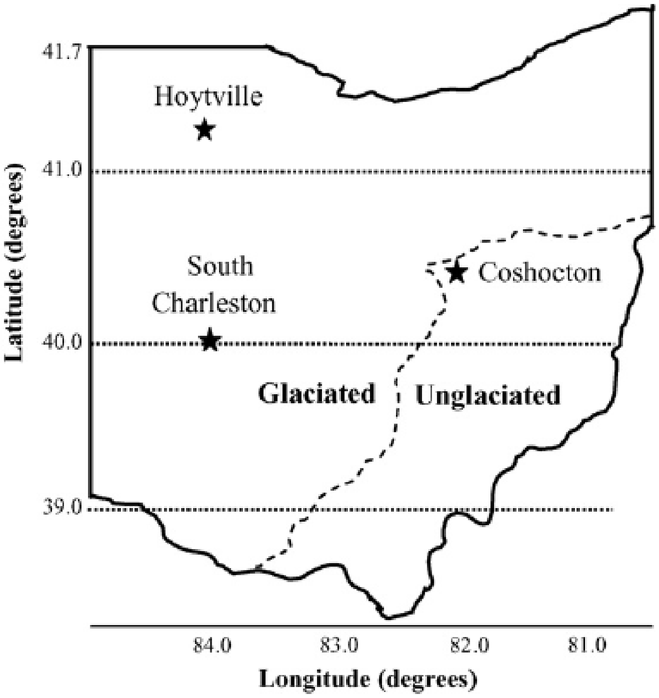

Figure 19. Sites in Blanco-Canqui et al. (2006b) Study on Soil Hydraulic Properties as Influenced by Corn Stover Removal from No-Till Management in Ohio

Figure 20. Conventional Tillage Corn Seeding Plot with Complete Removal of Corn Residues

Blanco-Canqui et al. (2006a) found soil hydraulic properties to be significantly affected with corn stover removal on a continuous corn no-till system over a single season of production. Higher rates of stover removal was correlated with a decrease in earthworm middens, increased bulk density, decreased soil water retention and transmission, and decreased air flow (Figure 22). The observations quantified in this study signify the rapid changes to soil physical properties, hydraulic activity, and productivity that can occur if crop residues are over appropriated from agricultural field.

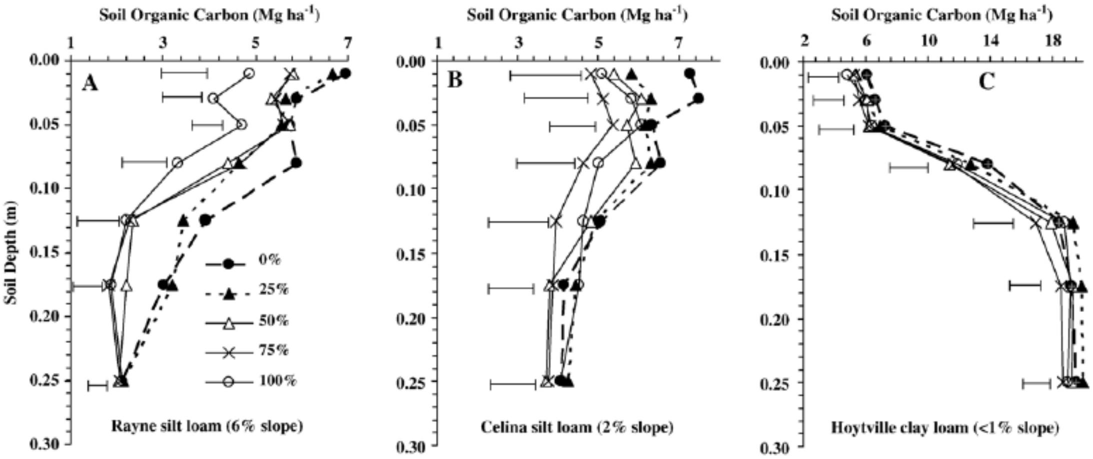

Figure 21. Depth Distribution of Soil Organic C as Affected by 5 Stover Removal Rates (Blanco-Canqui and Lal, 2007b)

The data on the effects of residue removal indicated that removal of residues at the rate of <1.25 Mg ha^{-1} may not be detrimental to soil quality. However, this finding cannot be extrapolated to all agricultural systems throughout the MRCSP region because this is a highly site-specific determination. Nonetheless, it does provide a ballpark estimate of sustainable crop removal which may be a guide for future research, and relevant information for land managers, planners and policy makers.

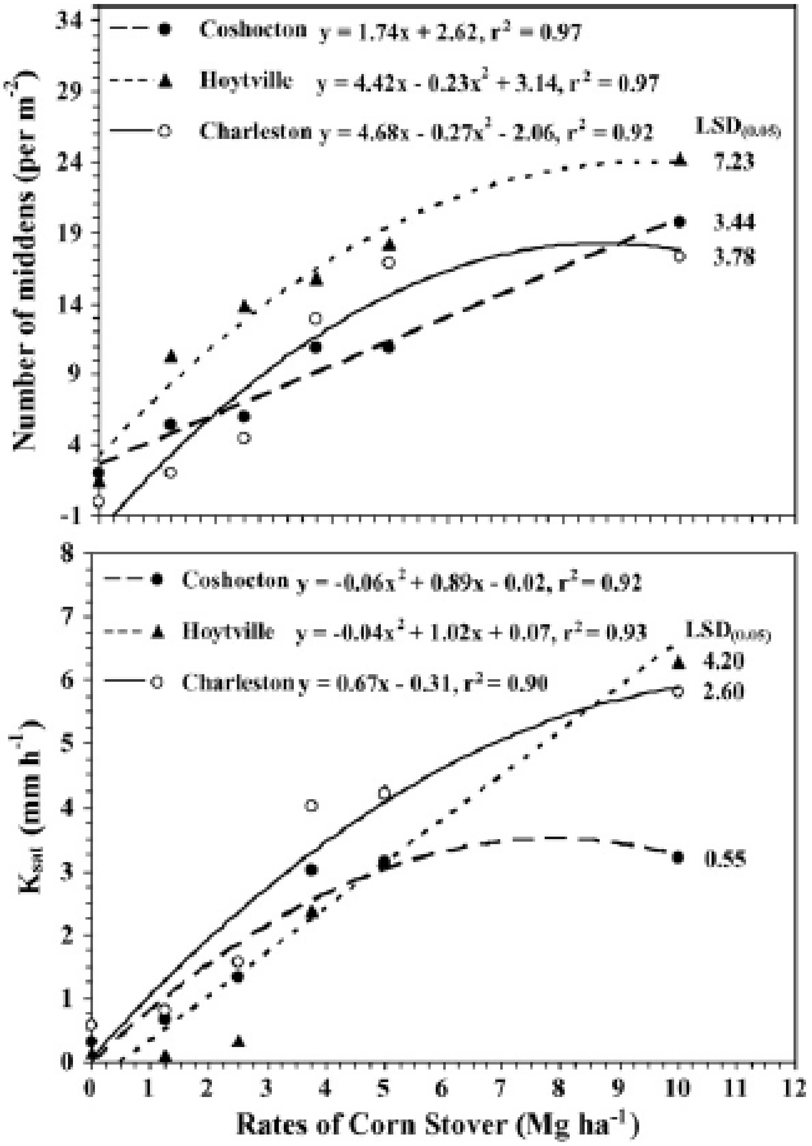

Figure 22. Earthworm Activity (Middens) and Geometric Means of Saturated Hydraulic Conductivity as a Function of Depth. Note decrease in earthworm activity and decrease in hydraulic conductivity with increasing stover removal. (Source: Blanco-Canqui et al., 2007a).

Highlighting the importance of regional variability on the impacts of crop residue removal also reported by Blanco-Canqui et al. (2006a) was that SOC concentrations declined rapidly in silt loams, however, SOC was not observed to be rapidly depleted in clay loam soils. Greater than 1.25 Mg ha^{-1} of crop residue removal produced negative results, and rapid detrimental effects were observed on all soils with 100% crop removal (Blanco-Canqui et al., 2006a). Residue removal has a significant impact on soil aggregation (Tables 11 and 12). Figure 23 shows the corn stover effect on the soil organic carbon at different locations of Ohio.

Table 11. Baseline Data on Soil Properties from Three Sites in Ohio (adapted from Blanco-Canqui et al., 2006a).

Soil Parameters	**Coshocton**	**South Charleston**	**Hoytville**
Soil Texture			
Sand (%)	29.0	22.2	22.6
Silt (%)	63.8	34.1	55.8
Clay (%)	15.3	43.7	21.6
Mean weight diameter of aggregates, mm	2.2	2.9	1.9
Total organic carbon (%)	3.0	2.6	2.8

Table 12. The Soil Organic Carbon (SOC) as Influenced by Different Level of Treatments for the Three Study Sites of OH (T10= 10 Mg ha^{-1}, T5 = Mg ha^{-1}, T3.75 = Mg ha^{-1}, T2.5 = 2.5 Mg ha^{-1}, T1.25 = Mg ha^{-1}, T0 = 0 Mg ha^{-1}; (adapted from: Blanco-Canqui et al., 2006a).

Rates of stover, Mg ha^{-1}	**TRT**	**Aggregate size, mm**						
		>4.75	**4.75-2**	**2-1**	**1-0.5**	**0.5-0.25**	**<0.25**	**$LSD_{0.05}$**
				g kg^{-1}				
Coshocton								
0	T0	22.9	24.7	25.9	25.7	26.0	17.5	3.7
1.25	T1.25	26.7	27.3	27.6	28.4	27.8	22.5	2.0
2.50	T2.5	27.0	27.0	28.5	29.5	29.6	23.0	1.6
3.75	T3.75	27.9	29.0	29.6	29.5	29.8	22.5	1.8
5	T5	27.9	29.2	29.6	29.8	29.9	22.0	1.2
10	T10	30.8	31.4	32.0	31.6	30.6	26.3	3.5
	$LSD_{0.05}$	4.7	4.8	4.2	5.4	5.6	5.3	
South Charleston								
0	T0	24.5	24.6	24.5	24.8	26.0	23.0	3.2
1.25	T1.25	25.5	25.2	25.5	24.9	26.3	20.1	1.7
2.50	T2.5	25.6	25.5	25.8	25.5	25.4	19.3	1.6
3.75	T3.75	26.4	26.1	26.2	26.0	26.4	20.2	2.1
5	T5	28.4	28.1	29.5	29.9	29.7	20.5	3.2
10	T10	28.8	28.4	28.9	29.1	29.1	18.9	5.0
	$LSD_{0.05}$	4.7	4.6	5.7	8.1	6.9	5.2	
Hoytville								
0	T0	24.6	26.4	24.8	24.5	24.2	19.3	2.2
1.25	T1.25	26.7	26.4	25.7	24.4	24.1	19.8	1.8
2.50	T2.5	26.5	26.0	26.2	24.9	25.9	19.6	0.9
3.75	T3.75	25.3	26.3	26.7	26.3	26.1	18.7	2.0
5	T5	25.9	25.9	24.8	24.9	24.2	17.9	1.7
10	T10	27.0	25.8	25.1	24.5	24.8	18.8	2.6
	$LSD_{0.05}$	3.6	3.1	2.9	1.7	2.3	1.8	

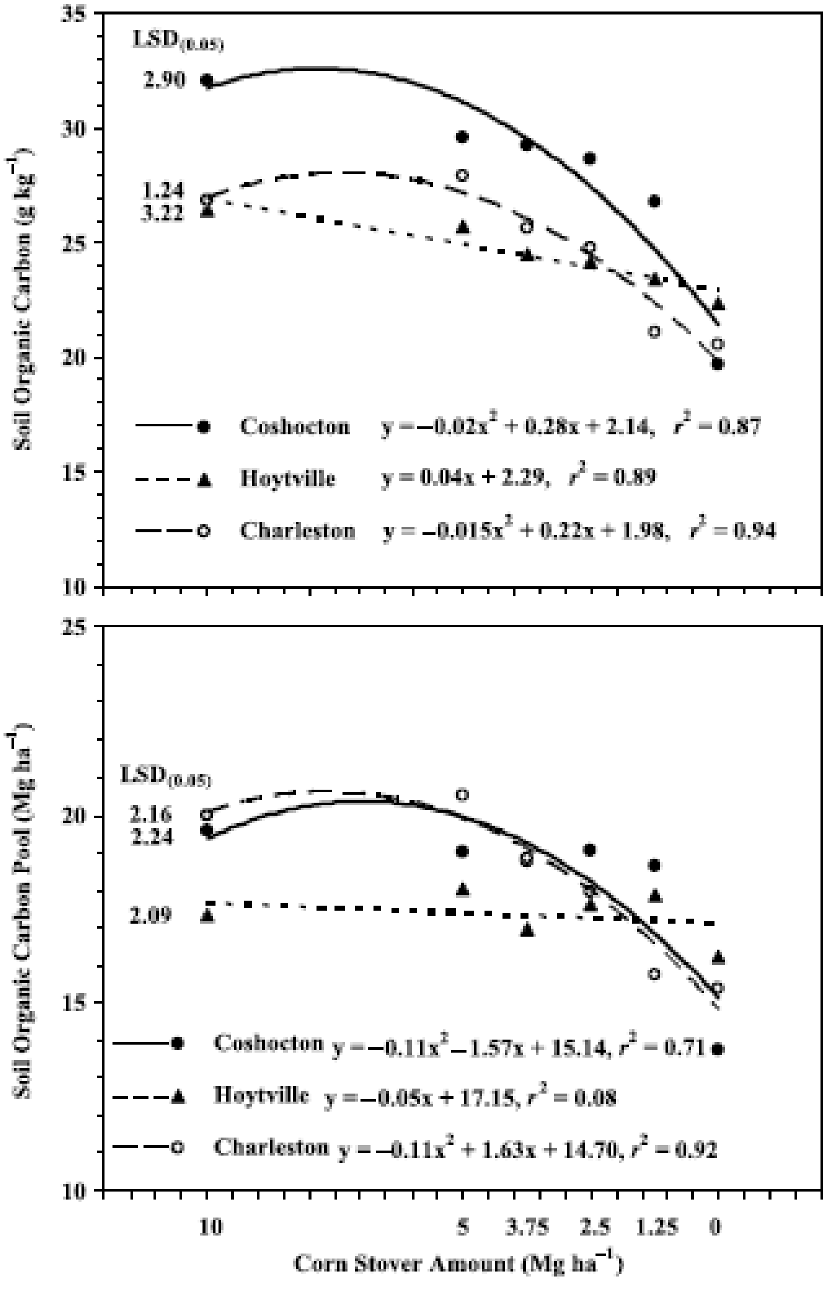

Figure 23. SOC vis-à-vis Amount of Corn Stover (Mg ha^{-1}) Remaining in Field (Source: Blanco-Canqui et al., 2006a).

Figure 24 shows the CT and NT plots. The corn yield and hydraulic conductivity were compared between CT and NT plots.

Figure 24. Field Tests Comparing Yields and Hydraulic Conductivity of No-Till Versus Conventional Tillage Plots

Crop residues are a vital resource with competing uses that must be carefully considered. The numerous studies presented here by the CMASC highlight the need for careful cost-benefit analyses and lifecycle assessments of various uses of crop residues. While bioenergy strategies are seen as useful measures for reducing dependence on fossil fuel resources and for mitigating climate change, negative aspects associated with removal of crop residue must also be considered. CMASC suggests that the most appropriate use of crop residues is to maintain and enhance soil carbon sequestration by increasing SOC, preventing erosion, increasing soil fauna, and improving global food security.

Production of bioenergy crops such as miscanthus, switchgrass, hybrid poplar, may offer important strategies for providing feedstock material for bioenergy platforms, however, the economic costs and environmental consequences of such production systems must also be carefully analyzed.

7. IMPACT OF ROTATIONAL TILLAGE ON SURFACE HYDROLOGY, SOIL ERODIBILITY AND SOC CONCENTRATION

A field study was conducted to assess the effects of rotational tillage on various soil characteristics and agronomic indices. Stavi et al. (2010) examined the impact of tillage for one growing season preceded by 3 years of NT, as a part of long-term rotational tillage strategy. The effect of rotational tillage was compared with that of the 10 consecutive years of NT. This study was conducted in Holmes County, eastern OH, to compare SOC and some key characteristics of the soil (Aquultic Hapludalfs), as well as some vegetational indices among continuous NT and rotational till-no-till (RO) systems, both under corn (*Zea mays L.*) at the time of the study. Soil properties were studied for 3 depths (0-6, 6-12 and 12-18 cm). Two fields were selected for the experiment, both under maize at the end of the 2008 growing season. Corn was at the same phenological stage (full maturity) in both fields. The RO field was disked in spring 2008 and planted to *Doblers* variety. Before disking, poultry manure was applied in early 2008 at 5 to 10 Mg ha^{-1}. Corn stover of the previous year (2007) was left on the surface as mulch during the winter.

The long-term farming system of the RO field was based on a rotation of 3-5 consecutive years of NT followed by 1 year of disking. The long-term rotation was followed to control incidence of weeds and pathogens. Corn variety *Pioneer 34D71* was sown in the NT field. Fertilizers included 340 l ha^{-1} of liquid ammonia with 28% N, and 95 l ha^{-1} of 10-34-0 applied just before sowing. Also in this field, management included stover retention on the surface as mulch during the winter. The long term strategy in the other field was consecutive NT, in order to control soil erosion. The rationale for selecting these two fields include the following: (i) same crop at the time of the study, (ii) a similar cropping history, (iii) similar slope gradient - 3° for RO and 2° for NT, and (iv) Coshocton soil series (fine loamy, mixed, active, mesic Aquultic Hapludalfs) for both fields.

Soil samples have also been collected from various counties in Ohio. The soil samples were taken and analyzed at three different depths: 0-10 cm, 10-20 cm and 20-30 cm. Three replicates of each sample's type were taken in a representative fashion. The plan is also to obtain soil samples from tillage plot on Amish farms in order to match the soil types and slopes of western Ohio fields (Table 13).

The data in Table 14 shows the preliminary results of the soil moisture, wet bulk density, and dry bulk density for the soils under no-till, conventional and rotational tillage practices. As expected, soil bulk density and moisture contents are generally higher in soils managed by no-till.

The results by Stavi et al. (2010) showed that RO adversely affects SOC pool and many other soil physical characteristics. Also infiltration rate, sorptivity, transmissivity, equilibrium infiltration rate, and cumulative infiltration were degraded following the RO (Table 13, Figures 25 through 27). Stavi and colleagues concluded that even one year of tillage following 3 years of NT adversely impacted the soil quality, and that degradation of soil quality negatively affected crop production. These changes illustrate the ease by which soil physical and hydrological degradation processes caused by tillage can occur. It is assumed that the actual effect of tillage on soil physical characteristics is even stronger than that observed, and may have been mitigated by the application of manure in the RO field before the growing season. In general, differences among the treatments were larger for the shallowest depth than in the middle and deepest depths (Table 14).

Table 13. Cropping History of Assessing the Effects of Rotational Tillage in Holmes County, Ohio (adapted from: Stavi et al., 2010)

Year	No-tillage	Rotational-tillage
1999	No-tilled pastures- hay	No-tilled pastures- hay
2000	No-tilled pastures- hay	No-tilled pastures- hay
2001	No-tilled pastures- hay	No-tilled pastures- hay
2002	No-tilled pastures- hay	No-tilled pastures- hay
2003	No-tilled pastures- hay	No-tilled pastures- hay
2004	No-tilled pastures- hay	Tilled corn
2005	No-tilled corn	No-tilled oats
2006	No-tilled Soybean	No-tilled alfalfa
2007	No-tilled Soybean	No-tilled corn
2008	No-tilled corn	Tilled corn

Table 14. Soil Penetration Resistance (PR: MPa), Field Moisture Capacity (Θc: g kg^{-1}), Moisture Content (Θg: g kg^{-1}), Bulk Density (P_b: g cm^{-3}), Total Water Stable Aggregate (WSA: g kg^{-1}), Mean Weight Diameter (MWD: mm), Soil Organic Carbon (SOC: g kg^{-1}), Total Nitrogen (TN: g kg^{-1}), and C:N Ratio, Associated with the Combinations of Treatment and Depth

Level	PR	Θc	Θg	P_b	WSA	MWD	SOC	TN	C:N ratio
P value	0.0001	0.6108	0.0001	0.0009	0.0002	0.0001	0.0001	0.0001	0.5840
NT, Shallow	0.42 c	431 a	261 a	1.20 d	887 a	4.3 a	24.9 a	2.50 a	10.0 a
NT, Middle	1.57 b	334 bc	220 b	1.35 c	838 a	3.3 b	18.2 b	1.81 b	10.0 a
NT, Deep	2.69 a	315 bc	210 b	1.39 bc	776 b	2.7 c	14.7 c	1.48 c	9.9 a
RO, Shallow	1.25 b	343 b	173 c	1.40 bc	461 c	1.3 d	15.9 bc	1.55 bc	10.3 a
RO, Middle	1.73 b	282 bc	207 b	1.44 ab	497 c	1.6 d	16.4 bc	1.62 bc	10.1 a
RO, Deep	2.35 a	256 c	207 b	1.50 a	466 c	1.5 d	15.6 bc	1.53 c	10.2 a

NT=No tillage. RO=Rotational till-NT practice.

Means within a column followed by different lower-case letters differ at the 0.05 probability level according to Tukey's Honest Significant Difference (HSD). Source: Stavi et al. (2010)

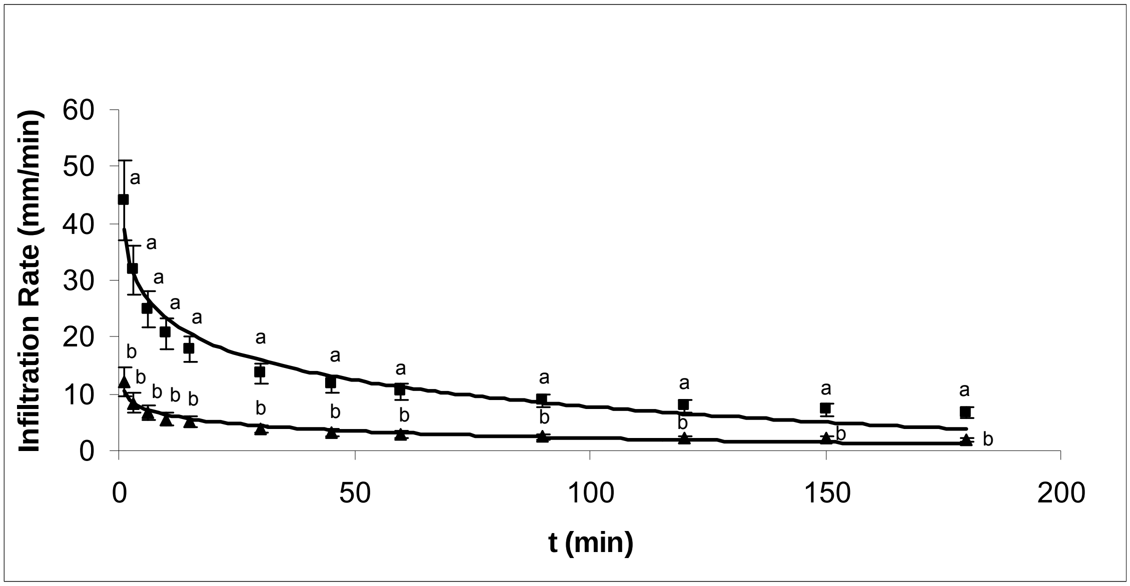

Figure 25. Mean Infiltration Rate (ί) According to Treatment. ■ – No Tillage (NT). ▲ - Rotational Till-NT Practice (RO). Means within a same time followed by different letters differ at the 0.05 probability level according to Tukey'sHSD. (Source: Stavi et al., 2010).

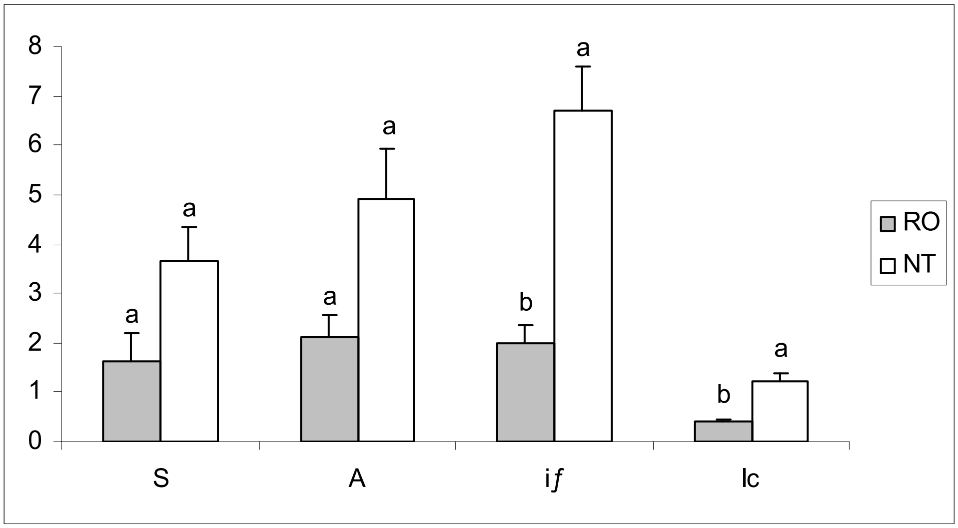

Figure 26. Mean Values of the Soil Sorptivity (*S*; cm min$^{-0.5}$), Transmissivity (*A*; mm min^{-1}), Equilibrium Infiltration Rate (ί*f*; mm min^{-1}) and Cumulative Infiltration (I*c*; m) According to Treatment. RO - Rotational Till-NT Practice. NT - No tillage. Means within a pair of bars followed by different letters differ at the 0.05 probability level according to Tukey'sHSD. (Source: Stavi et al., 2010).

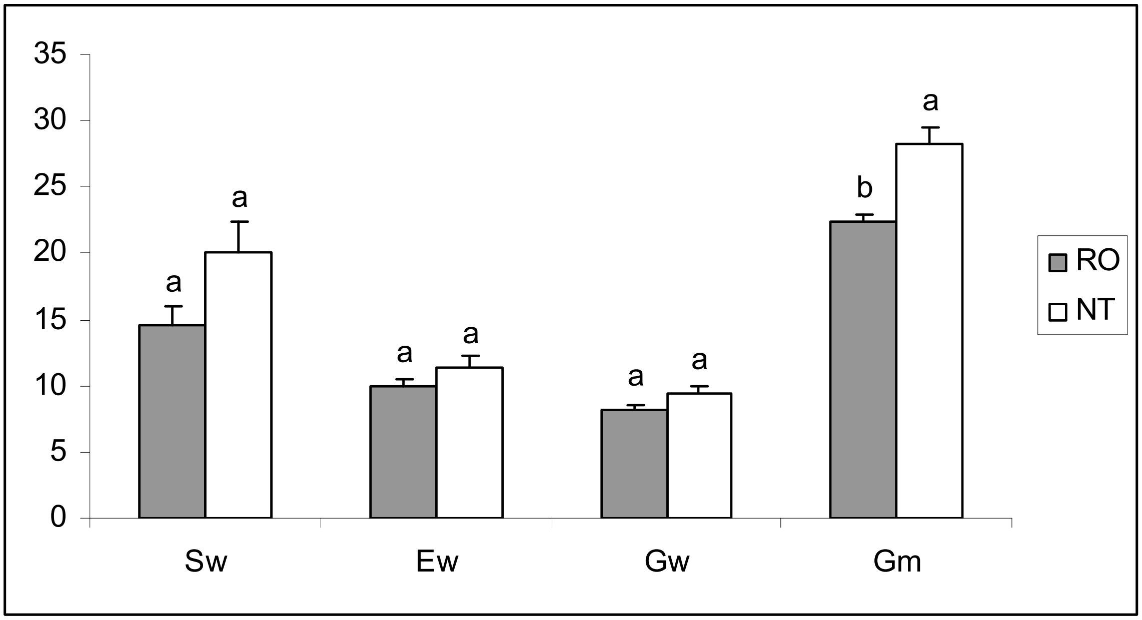

Figure 27. Mean Wet Stalk Biomass (S*w*; Mg ha^{-1}), Wet Ear Yield (Ew; Mg ha^{-1}), Dry Grain Yield (G*w*; Mg ha^{-1}) and Grains Moisture Content (G*m*; %) According to Treatment. RO - Rotational till-NT practice. NT - No tillage. Means within a pair of bars followed by different letters differ at the 0.05 probability level according to Tukey'sHSD. (Source: Stavi et al., 2010).

8. EFFECTS OF GRAZING IN ROTATION WITH CROPLAND ON SOC DYNAMICS

At the same region, Stavi et al. (2011) examined the impact of cattle grazing during the dormant season on soil quality. The study was conducted due to the fact that cattle feeding is widespread in the Midwest USA, as it is incorporated into the cropping system, either directly through in-situ grazing (Figures 28 and 29) or indirectly, through hay production (Figure 30). In this study, Stavi and colleagues referred to soil mechanical and hydrological characteristics and to herbaceous root biomass. Soil properties were measured in a paddock under rotational grazing during the growing season only (GR) and compared with those under grazing during the dormant season and rotational grazing during the growing season (DO).

Figure 28. Cattle Grazing in a Pastureland in Addition to Cropping (Holmes County, OH)

The study was conducted in Coshocton County, eastern Ohio, in sites comprised of Coshocton soil series (fine loamy, mixed, active, mesic Aquultic Hapludalfs). Two paddocks were selected for the study. One of the paddocks (GR) has been used for weekly-rotational grazing (cycles of 1 week on and 3 weeks off grazing) during the growing season (May - November) for the last 25 years. The second paddock (DO) has been used since the last 9 years (since 2000) for weekly-rotational grazing during the growing season and as monthly-rotational grazing (cycles of 1 month on and 1 month off) during the dormant season (December - April). The rationale of this grazing system lies in allocating one paddock for intensive use during the dormant season while maintaining relatively low stocking pressure in the remainder of the paddocks.

Figure 29. Horses Grazing in a Pastureland in Addition to Cropping (Holmes County, OH)

The mean surface incline ranges between 1 and 4° in DO compared with 3 and 6° in GR. The land area is 6 ha for DO and 3.8 for GR and the number of cattle grazed was 30 and 25, respectively. Annual fertilizers application of the paddock comprised of 4.5 Mg manure ha^{-1} in DO and 224 kg N ha^{-1} in GR, without any application of lime or gypsum in these paddocks. Cattle in DO are fed by 1,350 kg hay and 45 kg salt/minerals per week during the dormant season. Three plots were randomly selected in each paddock, 7 sites were randomly selected for soil sampling in each plot, and soil was sampled at 3 depths in each site.

Figure 30. Harvested Hay Field (Holmes County, OH)

The results obtained by Stavi et al. (2011) reveal that livestock grazing during the dormant season caused strong adverse effects of herbaceous root biomass on soil physical and hydrological characteristics (Table 15). Also infiltration rate, sorptivity, transmissivity, equilibrium infiltration rate, and cumulative infiltration were degraded following grazing in the dormant season, as compared with the growing season (Figures 31 and 32). Adverse changes in these properties decreased soil quality and increased soil erosion risks. Nevertheless, the soil shear strength was not affected by grazing treatment.

Stavi and colleagues concluded that allocating one paddock for grazing in the dormant season helps in sustaining soil quality in other paddocks, and reduce the risk of accelerated soil erosion. They added that a system comprised of a series of paddocks for rotational grazing during the growing season and one or a few paddocks allocated for grazing during the dormant season is a rational strategy. Information about the published paper is included in Appendix C.

Table 15. Soil Penetration Resistance (PR: MPa), Moisture Content (Θg: g kg^{-1}), Bulk Density (Pь: Mg m^{-3}), Coarse (> 1 mm) Root Biomass (RB: mg cm^{-3}), Total Water Stable Aggregates (WSA: g kg^{-1}), Mean Weight Diameter (MWD: mm), and Volumetric Field Moisture Capacity (Θc: %), Associated with the Combinations of Treatment and Depth

Level	PR	Θg	Pь	RB	WSA	MWD	Θc
***P* value**	0.8441	0.0001	0.0339	0.0001	0.0417	0.0449	0.8103
GR, Shallow	0.54 d	377 a	0.98 d	33.0 a	938 a	4.5 ab	47.3 a
GR, Middle	0.94 c	291 b	1.32 c	3.6 c	906 ab	4.2 b	41.0 abc
GR, Deep	1.33 b	233 c	1.43 b	1.7 c	795 c	3.2 c	35.9 c
DO, Shallow	1.05 c	299 b	1.22 c	16.7 b	928 a	4.9 a	44.2 ab
DO, Middle	1.43 b	228 c	1.54 ab	2.2 c	860 bc	4.3 b	38.6 bc
DO, Deep	1.77 a	225 c	1.55 a	2.5 c	701 d	3.0 c	35.2 c

GR – Paddock for weekly-rotational grazing in the growing season.
DO – GR with frazing also during dormant season. Source: Stavi et al. (2011)

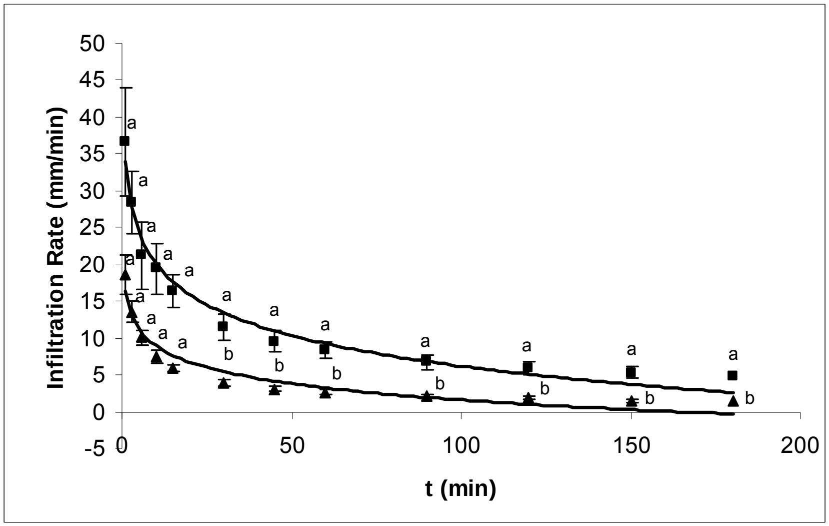

Figure 31. Mean Infiltration Rate (I*t*) According to Treatment. ■ – Paddock for Weekly-Rotational Grazing in the Growing Season (GR). ▲ - Paddock for weekly-rotational grazing in the growing season and monthly-rotational feeding in the dormant season (DO). Means within a same time followed by different letters differ at the 0.05 probability level according to Tukey'sHSD. (Stavi et al., 2011).

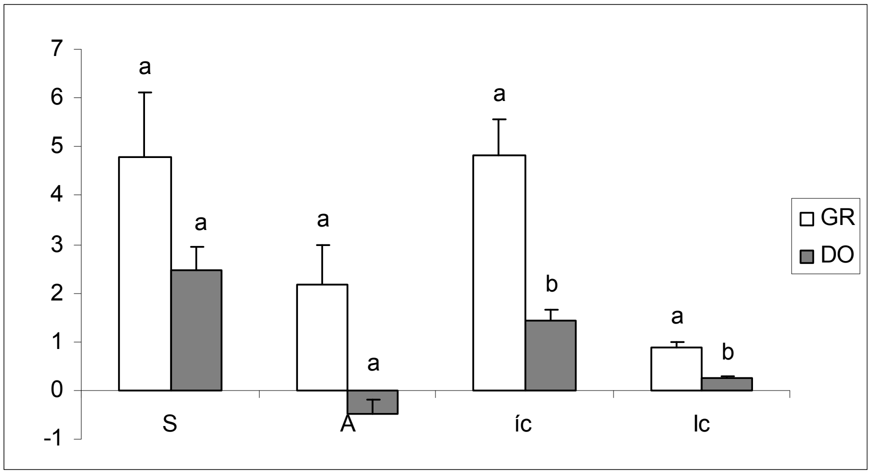

Figure 32. Mean Values of the Soil Sorptivity (*S*; cm min$^{-0.5}$), Transmissivity (*A*; mm min^{-1}), Equilibrium Infiltration Rate (í*c*; mm min^{-1}) and Cumulative Infiltration (I*c*; m) According to Treatment. GR – Paddock for Weekly-Rotational Grazing in the Growing Season. DO - Paddock for weekly-rotational grazing in the growing season and monthly-rotational feeding in the dormant season. Means within a pair of bars followed by different letters differ at the 0.05 probability level according to Tukey'sHSD. (Source: Stavi et al., 2011).

9. SOIL EROSION AND SOIL QUALITY IN RELATION TO CARBON POOL

Physical degradation of the soil increases its susceptibility to erosion by water action. However, there are few studies which have emphasized the effects of soil erosion on the resistance vs. susceptibility of the soil to further erosion. Thus, Stavi and Lal (2011) examined the effects of water-induced soil erosion on its susceptibility to further erosion, through the attendant changes in SOC and some other key characteristics of the soil. The study was conducted in a long-term (25 years) continuous NT corn field in central Ohio. Soils are comprised of various glacial deposits, covering the underlying bedrock. Soil series in the studied field are comprised of Crosby silt loam and Kokomo salty clay loam. While the Crosby soil occurs in the ridges, the Kokomo soil occurs mainly in the lower parts of the watersheds (USDA-SCS, 1980). Observations in the farm lands revealed the occurrence of gradual change from Crosby soil in the summits to Kokomo in the bottoms. Some sites in this field have regularly experienced rill and interrill erosion following intense rain showers during the winter and the growing season.

Corn was planted in mid April and harvested in mid October. The field was fertilized with un-processed cattle manure during the winter. Despite NT, the soil surface has experienced some degree of homogenization due to machinery traffic. Hence, the erosion processes are seasonal and of light to moderate severity. Yet, signs of rill and interrill erosion are apparent in some parts of the field. Surface survey revealed that the soil erosion is predominantly determined by small changes in surface incline (1-2°). A comparison of SOC concentration and some key characteristics of the uppermost soil layer (0-5 and 5-10 cm depths) was made between sites prone to interrill erosion (ER) and un-eroded sites (UN), comprised of the Kokomo soil series.

The results obtained by Stavi and Lal (2011) reveal that the loss of the highly productive topsoil by erosion caused a considerable depletion of the SOC concentration and soil physical quality. This was evident by the degraded characteristics of the remaining soil following the erosion process. The degraded physical quality of the soil in ER increases its susceptibility to accelerated erosion. At the vertical aspect, the removal of the more stable topsoil, exposes the more erodible subsoil. This was evident by the significantly higher erodibility of the sub-soil than the surface soil. In general, the effect of erosion on soil characteristics decreased with increase in soil depth. Stavi and Lal (2011) proposed that a positive feedback occurs in which the larger the physical degradation of the uppermost layer of the soil due to water erosion, the more it is susceptible to accelerated erosion (Table 16, Figure 33).

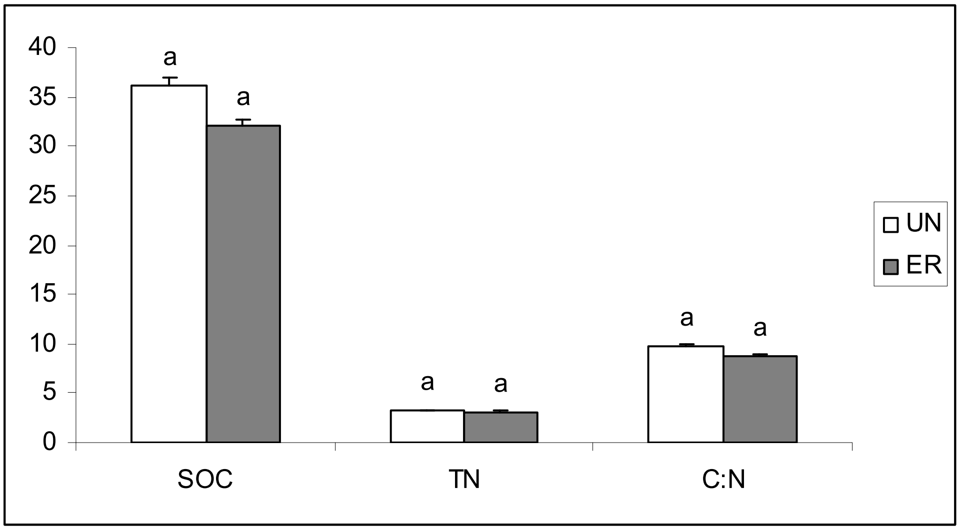

Figure 33. Mean Values of the Soil Organic Carbon (SOC: g kg^{-1}), Total Nitrogen (TN: g kg^{-1}), and C:N Ratio (C:N), According to Site. UN - Uneroded Sites. ER – Eroded sites. Means within a pair of bars followed by different letters differ at the 0.05 probability level according to Tukey'sHSD. (Source: Stavi and Lal, 2011).

Table 16. Mean Soil Penetration Resistance (PR: MPa), Gravimetric Moisture Content (Θ*g*: g kg^{-1}), Bulk Density (ρь: Mg m^{-3}), Soil Organic Carbon Concentration (SOC: g kg^{-1}), Total Nitrogen Concentration (TN: g kg^{-1}), C:N Ratio (C:N), and Erodibility Factor (K factor: [ton ha h]/[ha MJ mm]), Associated with the Combinations of Site and Depth

Level	**PR**	**θc**	**P_b**	**SOC**	**TN**	**C:N ratio**	**K factor**
***P* value**	0.5320	0.3749	0.7192	0.0134	0.4360	0.0808	0.0222
UN, 0-5 cm	4.28d	290a	1.28c	40.7a	3.6a	10.9a	0.00281c
UN, 5-10 cm	4.78b	282a	1.38b	31.5c	3.0c	8.5c	0.00372a
ER, 0-5 cm	4.56c	256b	1.39b	35.4b	3.4b	9.6b	0.00323b
ER, 5-10 cm	5.13a	252b	1.50a	28.8d	2.8c	7.7d	0.00385a

UN – Uneroded sites. ER – Eroded sites. Source: Stavi and Lal (2011).

10. CARBON SEQUESTRATION AND SOIL QUALITY IMPROVEMENT POTENTIAL OF RESTORED TALLGRASS PRAIRIE IN OHIO

Another study, conducted in central Ohio, aimed to assess the C sequestration and soil quality improvement potential of restored tallgrass prairies (Beniston and Lal, 2010). The objective was to determine the ability of prairie plantings to restore SOC and important agronomic functions to degraded soils. This study analyzed C and N contents and a suite of soil physical parameters among created prairies of different ages (i.e., 8, 13, and 31 years), and compared them to adjacent cultivated land and a lawn.

Soils under the long term prairie (P77) contained linear increases in SOC (Figures 34 and 35) and significant improvement in all of the soil physical properties measured in the soil surface layer (0-10 cm). The prairie treatments exhibited great increases in soil aggregate mean weight diameter (MWD) (Figure 35) to a depth of 30 cm. Aggregation is a key soil characteristic, which affects most other physical and biological properties of the soil, and equilibrium levels of aggregation were achieved after only 8 years after tallgrass prairie restoration. The long-term prairie treatment demonstrated significant increases in plant available water, total porosity, and particulate organic matter C, and significant decreases in bulk density in the soil surface (0-10 cm; Table 17). Particulate organic matter (POM) is a measure of plant residues accumulating in the soil. It serves as a basic food source for the soil food web, as a source of plant nutrients, and is considered a key soil quality parameter. The increases in POM-C found under prairie treatments can be viewed as an indication of a healthy soil ecosystem.

Data from this study indicate that planting tall-grass prairie is a viable option for restoring soil quality and SOC in degraded soils. Currently, there is widespread interest in the potential of prairie grasses to be grown as biomass crops. The study suggests that prairie grasses will not only produce large quantities of biomass, but will improve a range of important soil-mediated ecosystem processes.

Table 17. Soil Physical Quality Parameters (0 – 10 cm)

Treatment	**ρ_b**	**AWC**	**f_t**	**POM-C**
31 Yr Prairie (P77)	1.11 (.04)B	1.9(.20)A	.56(.02)A	14.09(1.19)A
13 Yr Prairie (P95)	1.32(.04)A	1.4(.20)AB	.46(.02)BC	5.95(1.19)B
8 Yr Prairie (P00)	1.29(.04)A	1.6(.20)AB	.47(.02)B	6.21(1.19)B
Agriculture (AG)	1.46(.04)A	1.1(.20)B	.37(.02)D	3.29(1.19)B
Lawn (LA)	1.36(.04)A	1.5(.20)AB	.39(.02)CD	4.11(1.19)B

Notes: Soil physical properties analyzed at the 10cm depth, bulk density ρ_b (g cm^{-3}), available water capacity AWC (cm of available water), total porosity f_t (cm^3 cm^{-3}), and particulate organic matter C POM-C (g C kg^{-1} soil). Values labeled with different letters indicated statistical differences when analyzed with a 1-way ANOVA and Tukey's HSD test (0.05). Source: Beniston and Lal (2010).

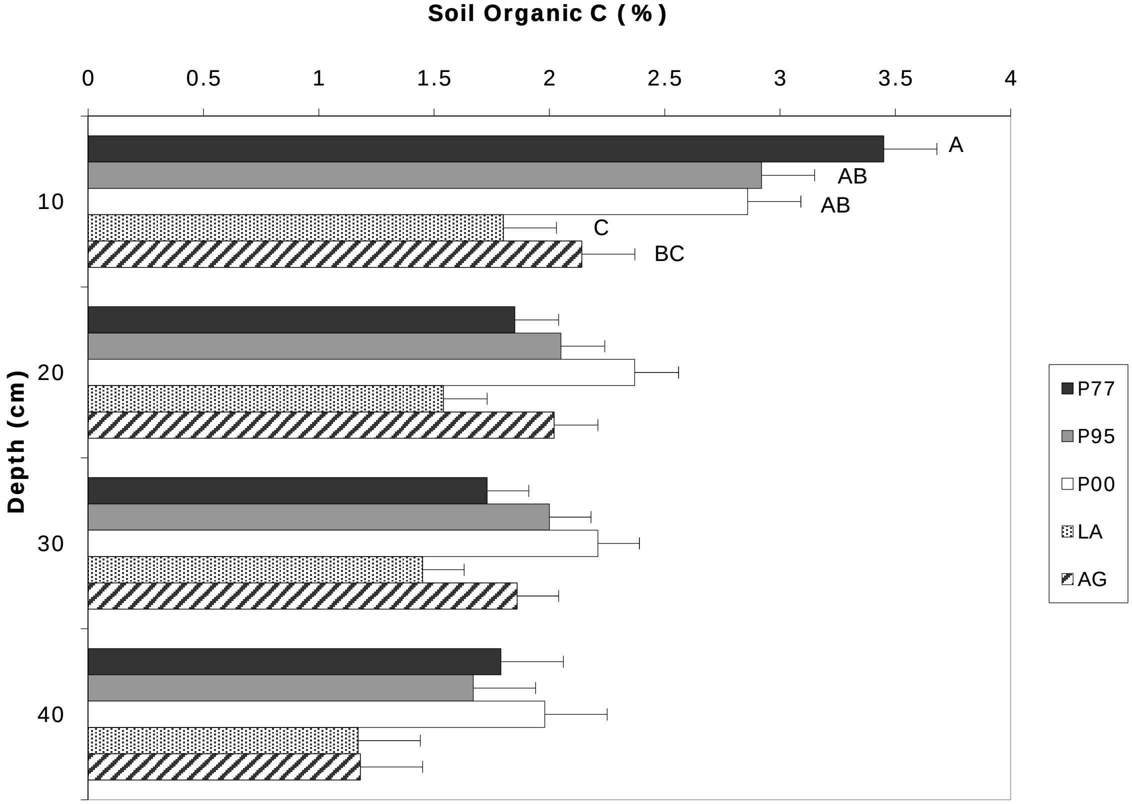

Figure 34. Depth Profile SOC Concentration (%). Values are means from a 1-way ANOVA testing the effect of treatment at each depth. Error bars represent standard errors. Capital letters indicate t-groupings, or groups that are significantly different, in Tukey's Honest Significant Difference (HSD) test (∝ = 0.05). (Source: Beniston and Lal, 2010).

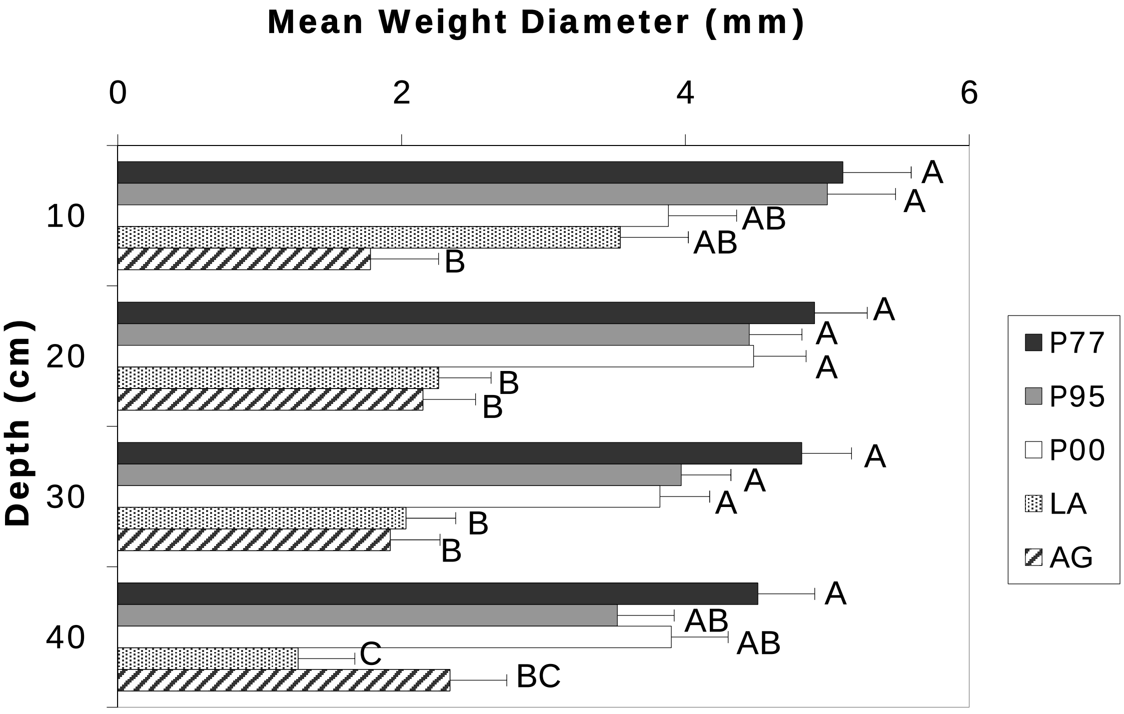

Figure 35. Depth Profile of Aggregate Mean Weight Diameter (mm). Values are means from a 1-way ANOVA testing the effect of treatment at each depth. Error bars represent standard errors. Capital letters indicate t-groupings, or groups that are significantly different, in Tukey's Honest Significant Difference (HSD) test(∝ = 0.05). (Site list Table 14) (Source: Beniston and Lal, 2010).

11. MODELING THE IMPACTS OF CARBON SEQUESTRATION IN TERRESTRIAL SYSTEMS AND IMPLICATIONS FOR CARBON TRADING

11.1 Modeling Soil C Pool and Changes Due To Management

Geographical information system (GIS) based modeling was done using easily available data sources such as national soil characterization data, soil maps, land use maps, crop data, and tillage data with the following objectives:

(1) To predict and map the regional soil C pool at various scales,

(2) To identify factors affecting the geographical distribution of soil carbon pool,

(3) To quantify the change in soil carbon pool due to no-till adoption and land use changes at various scales, and

(4) To identify and map the carbon sequestration potential of soils in the MRCSP region for future soil carbon sequestration and carbon credit trading programs

Techniques used in GIS modeling includes spatial interpolation methods such as kriging, regression kriging, geographically weighted regression (Mishra et al., 2009; 2010a), modeling with vector based overlay analysis (Tan et al., 2006), and modeling with raster based overlay analysis (Mukundan et al., unpublished). Information on the published results of these studies is included in Appendix C.

A change from conventional tillage to NT in the MRCSP region can significantly build up SOC and thereby aid in mitigating the buildup of atmospheric CO_2, and mitigating global climate change. Since 1990, there has been a tremendous increase in the percentage of cropland under NT in the agriculturally dominant regions of the Midwestern U.S. due to a change from conventional tillage to conservation tillage practices. In Ohio, the NT practice management has been increased from around 13% in 1989 to about 50% by 2008. The associated decrease in conventional tillage dropped from 57% in 1989 to about 33% by 2008 (Figure 36). The rate of change in SOC through best management practices (BMPs) needs to be documented at different scales to assess the effectiveness of these practices

> ***"Soil carbon sequestration is a vital process in combating global climate change. Studies have shown that agricultural soils have huge potential to store C and thus drawing down atmospheric CO_2 levels."***

and for future C sequestration and C credit trading programs. As per article 17 of the 1997 Kyoto Protocol, C can be tracked and traded like any other commodity, creating another income stream for farmers.

In the U.S., various regional and state level C offset programs are being developed such as the Regional Greenhouse Gas Initiative (RGGI), California Climate Action Registry, and the Chicago Climate Exchange (CCX). The CCX program offers C credits called Carbon Financial Instruments (CFI) which may be traded amongst the member companies. Companies that fail to reduce emissions may purchase credits from those who make extra credits through emission cut or from verified offset projects. One such offset program offered by the CCX is CFI contracts to implement conservation tillage that sequester at a rate of ~ 0.5-1.5 Mg of CO_2 ha^{-1} yr^{-1} for soil C sequestration projects. Such programs can provide incentives to farmers willing to adopt conservation tillage practices and at the same time improve soil quality and environmental sustainability.

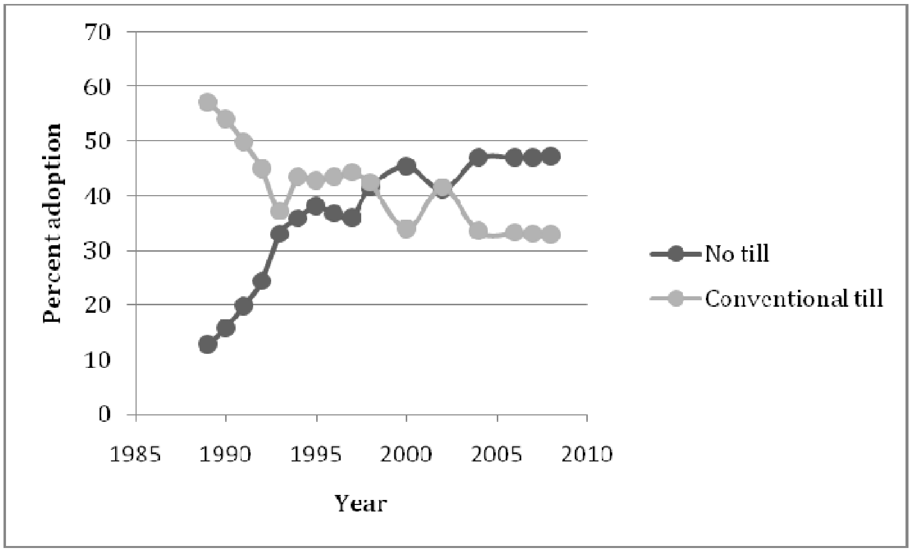

Figure 36. Trend in Tillage Practices in the State of Ohio (CTIC, 2008)

Monitoring change in SOC can use both direct and indirect methods. Direct methods involve field and lab measurements of SOC content, bulk density, sampling depth, and rock fragment fraction to estimate C content in kg m^{-2}. Direct methods can only be used at the field or plot scale; and for estimating C pool at regional or global scales, spatial interpolation of point data measurements may be required. These include methods such as geostatistical interpolation and use of geographical information systems (GIS).

11.2 Terrain Modeling using Geostatistical Methods

Umakant Mishra used geostatistical methods to predict and map SOC pools at different soil depth intervals. This method was tested for the state of Indiana as a case study. Results of this study are presented in Figures 37 and 38. Information about the published paper is included in Appendix C. Mishra et al. (2009) concluded that prediction of SOC pool and its spatial variability is possible using geostatistical approach and that the method may be adopted at different scales.

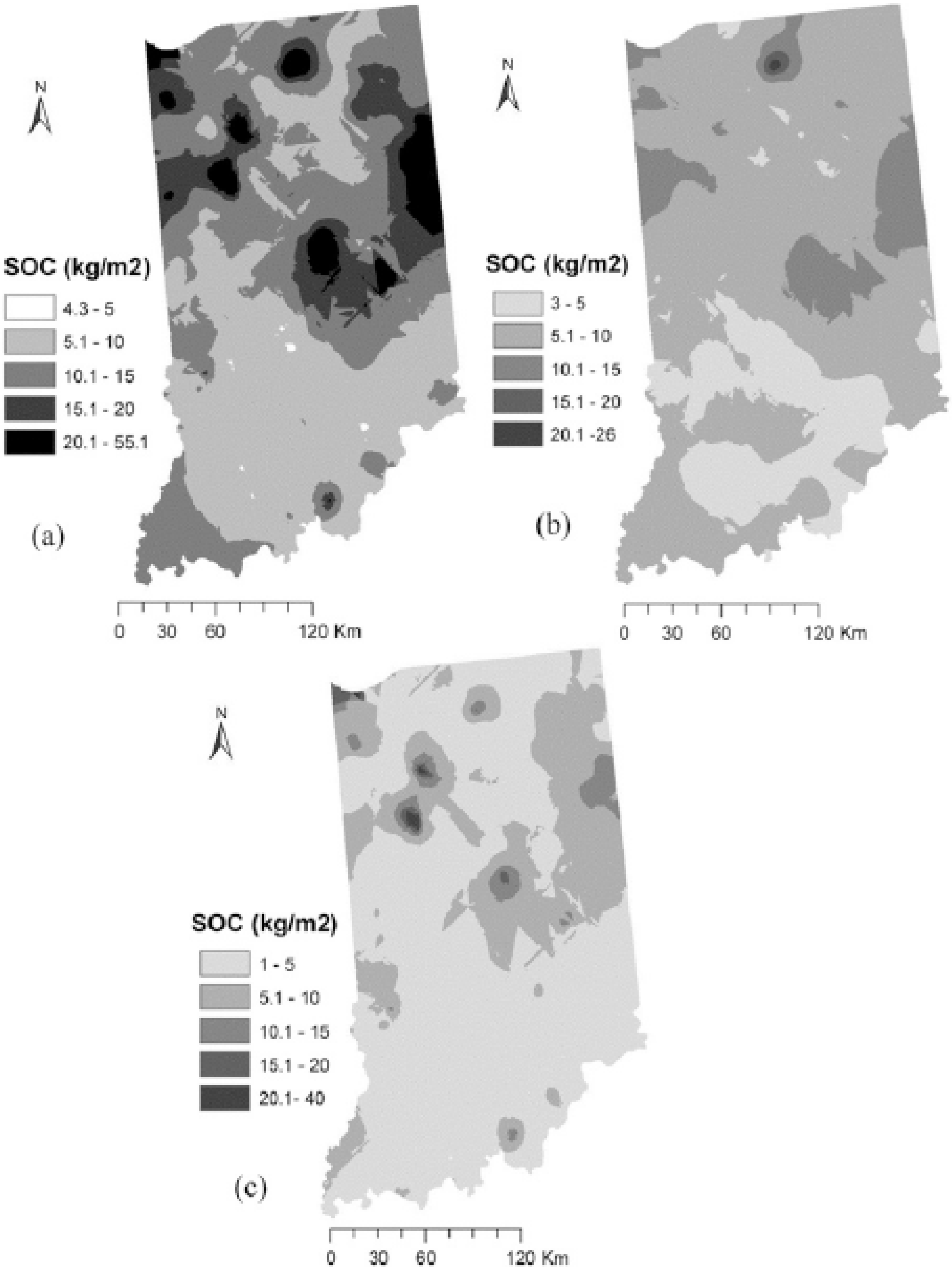

Figure 37. Predicted SOC Pool Maps for (a) 0 to 1, (b) 0 to 0.5, and (c) 0.5 to 1.0 m (Source: Mishra et al., 2009).

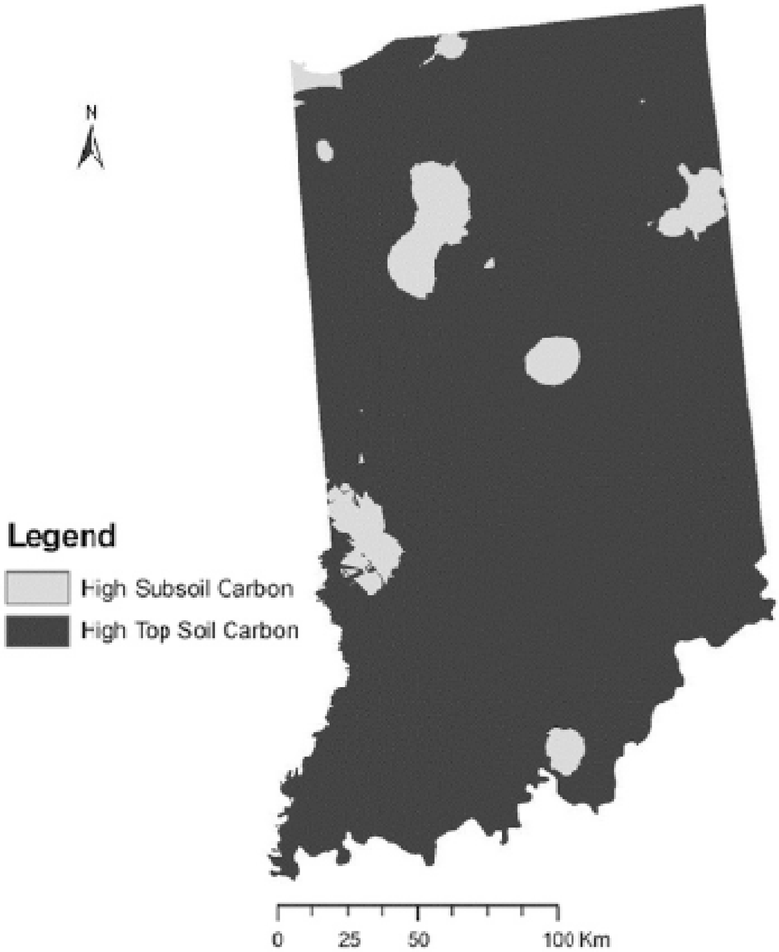

Figure 38. Regions of High Topsoil SOC and High Subsoil SOC in the State of Indiana (Source: Mishra et al., 2009)

11.2.1 Geospatial Data and Soil Carbon Sequestration Potential Prediction. Tan et al. (2006) used field experimental and geospatial data to estimate the C sequestration potential for the MRCSP project region. They predicted a 17% increase in the SOCP over a period of 20 years in the upper 30 cm soil due to a change from conventional tillage to NT. The state of Ohio was found to be one of the top contributors to this change accounting for almost 26% of the total change (Table 18; Figure 39). However, uncertainties in C sequestration rates due to differences in cropping pattern and baseline C content were not included in the simulation. Tan et al. (2006) concluded that baseline SOC content is an indicator of C sequestration potential with NT practices (total sequestration capacity tends to be greater in soils with higher SOC content with conversion from CT to NT).

Table 18. Baseline SOCP and Changes in SOCP with Conversion from CT to NT Between 1992 and 2012 (Source Tan et al., 2006)

State/region	SOCP (Mg C ha-1) 1992		NT 2012	CT 2012	Increased SOC[†]	Contributed by each state
	Mean[‡]	Std. error	Mean[§]	Mean[¶]	Tg	%
Indiana	67.7	2.0	72.6	61.3	49.8	36.6
Kentucky	35.4	0.4	40.3	34.3	6.4	4.7
Maryland	41.4	2.2	46.3	39.4	1.8	1.3
Michigan	74.6	1.7	79.2	66.8	39.7	29.2
Ohio	62.5	0.7	67.8	57.3	35.0	25.7
Pennsylvania	32.6	0.3	37.4	31.9	2.9	2.1
West Virginia	28.8	0.6	33.4	28.5	0.5	0.4
MRCSP	64.0	0.7	67.6	57.1	136.0	100.0
Std. error	0.7		0.7	0.6	19.2	

[†] Cumulative SOC gains with adoption of NT on the projected cropland area by 2012. Tg = 10^{12} g.

[‡] Baseline SOCP on all croplands as of 1992.

[§] Soil organic C pools by the year 2012 were computed using Eq. (2), and the variations are associated with the baseline SOCP in 1992.

[¶] Soil organic C by the year 2012 were computed using Eq. (3), and the variations are associated with the baseline SOCP in 1992.

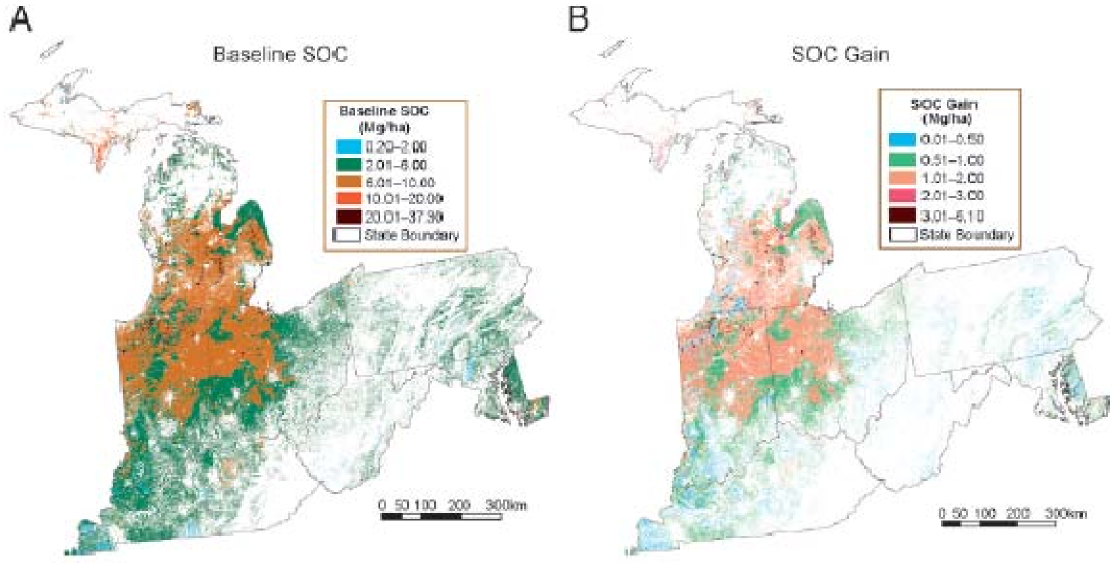

Figure 39. A-Baseline Carbon Content; B- Simulated Gain in SOC Following Change in Cropland from CT to NT Between 1992 to 2012 (Source: Tan et al., 2006)

11.2.2 Predicting Soil C Pool on County Basis. Soil C pool change is a function of baseline soil C content, cropping pattern and management practices and, therefore, it is important to quantify the changes taking place in all of these factors. It is also necessary to quantify the total change in soil C pool while simultaneously identifying regions for future C sequestration potential under the current land use scenario. Although studies have been conducted to estimate C pools and quantify changes in SOC, very few studies explained the spatial and temporal relationship in soil C sequestration. A study conducted by Mukundan under the auspices of MRCSP used readily available data sources such as soil maps, crop layer data, and tillage data to quantify the change in soil C pool for the state of Ohio during the period from 1990 to 2010 and to identify potential regions for future soil C sequestration.

Results indicated that the baseline soil organic carbon pool (SOCP) was about 534 Tg for the surface soil layer of depths ranging from 8 cm to 51 cm (Figure 40). A maximum of 7.5% potential increase in SOCP in the surface soil was possible through no-till management under the current land use scenario of which 5.4% was attained with the current level of no-till adoption. Opportunity exists for an additional 11 Tg of soil C sequestration through better adoption of no-till practices (Figures 41 and 42). Soil C sequestration potential shows spatial dependency that may be due to the effect of biotic and abiotic factors (Figure 43). Regions in Ohio with the highest and lowest soil C sequestration potential were identified in MLRAs and county maps. A similar approach may be used for the whole MRCSP region. Specific MLRAs and counties can be considered as various scenarios for C sequestration potential that needs to be identified and mapped.

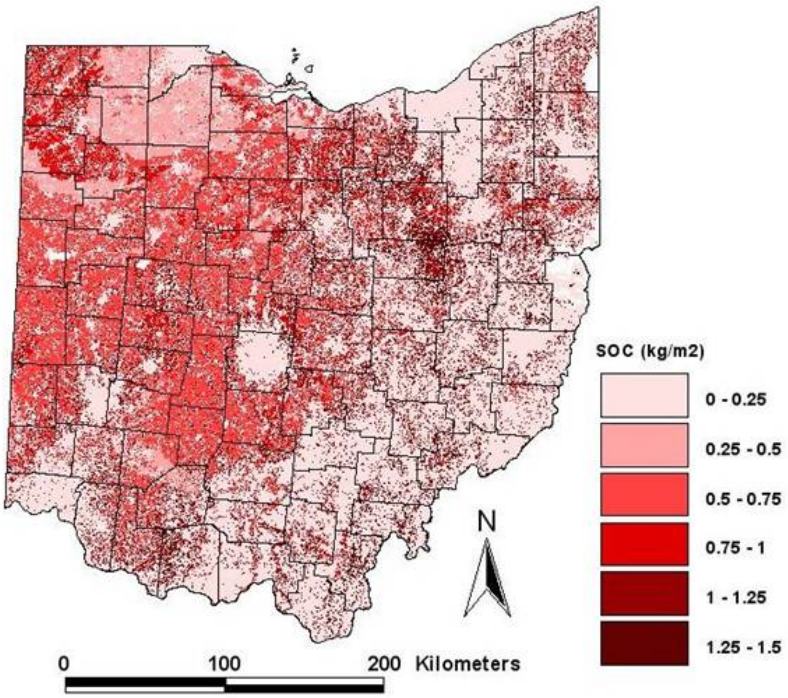

Figure 40. Map of Ohio State Showing Increase in SOCP Between 1990-2010
Source: Mukundan et al., 2009 (unpublished)

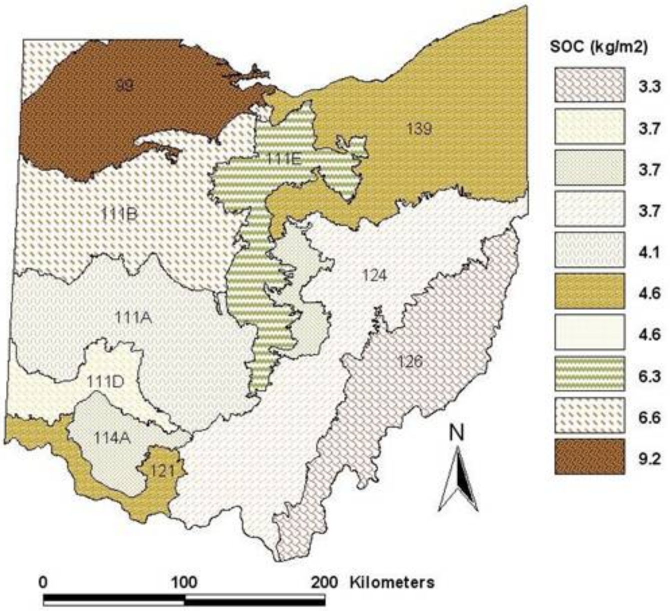

Figure 41. MLRA Map Showing Baseline Mean SOCP
Source: Mukundan et al., 2009 (unpublished)

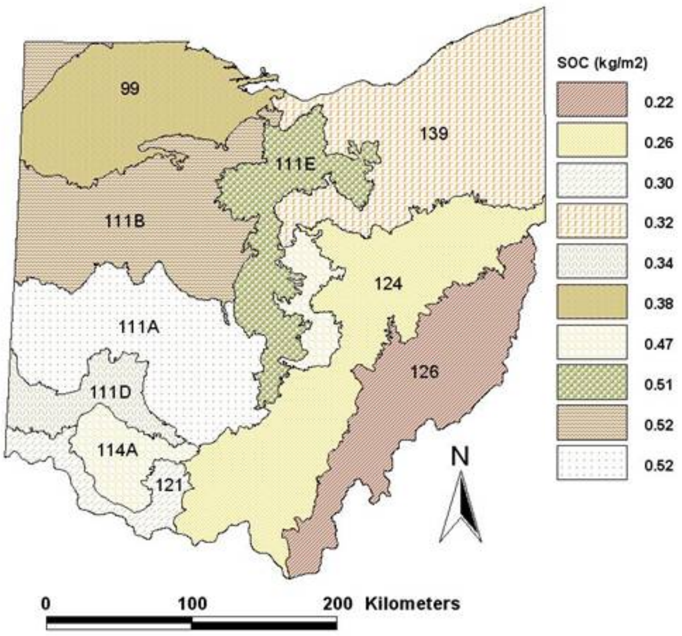

Figure 42. MLRA Map Showing Mean Increase in SOCP Between 1990-2010
Source: Mukundan et al., 2009 (unpublished)

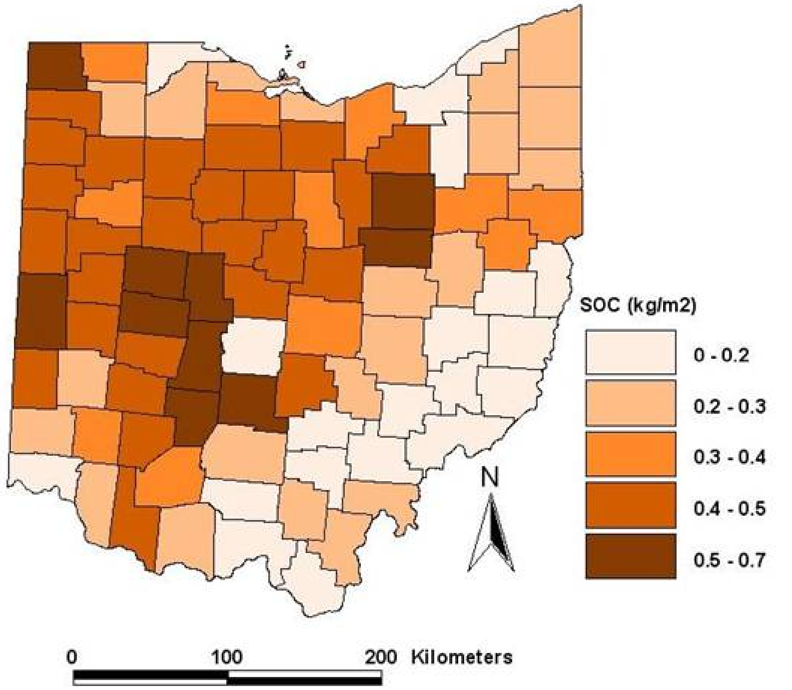

Figure 43. County Map Showing Mean Increase in SOCP Between 1990-2010
Source: Mukundan et al., 2009 (unpublished)

The soil C sink capacity is determined by physiographic sector including soil type drainage, and climate. The data supports the conclusion that an optimum combination of baseline soil C, land use, and management practices can maximize soil C sequestration potential. Future soil C sequestration and other C offset programs require development of optimum land use change scenarios for maximizing terrestrial C sequestration while maintaining environmental sustainability. This may be accomplished using a coarser to finer resolution approach for soil C pool estimation and identifying regions for future agriculture soil C sequestration potential. Analysis at the MLRA scale can identify potential regions for C sequestration at a coarser scale. More detailed analysis of potential regions can be done using county maps.

For state level estimation of C pool and identifying potential regions for C sequestration, less detailed soil maps may be used without compromising much accuracy. Detailed soil maps may be useful for sub-county level mapping of SOCP.

In other studies conducted by Mishra et al. (2010), Kumar and Lal (2010) and Kumar et al. (2010) different geostatistical methods (e.g. OK, MLR, RK, GWR) were used to predict and map the SOC pools at different soil depth intervals for different states. These methods were tested for the Midwestern region including seven states (Indiana, Michigan, Ohio, Maryland, Pennsylvania, Kentucky and West Virginia) as a case study. From these studies, it was concluded that prediction of SOC and its spatial variability is possible using geostatistical approach, and the methods can be adopted at different scales.

The values for the estimated SOC pool for Indiana, Michigan and Ohio were 0.90 Pg, 1.9 Pg and 742 Tg, respectively. Figure 44 shows the distribution of SOC pool up to 1-m depth for Michigan. Figure 45 shows the distribution of SOC pool with depth for Michigan.

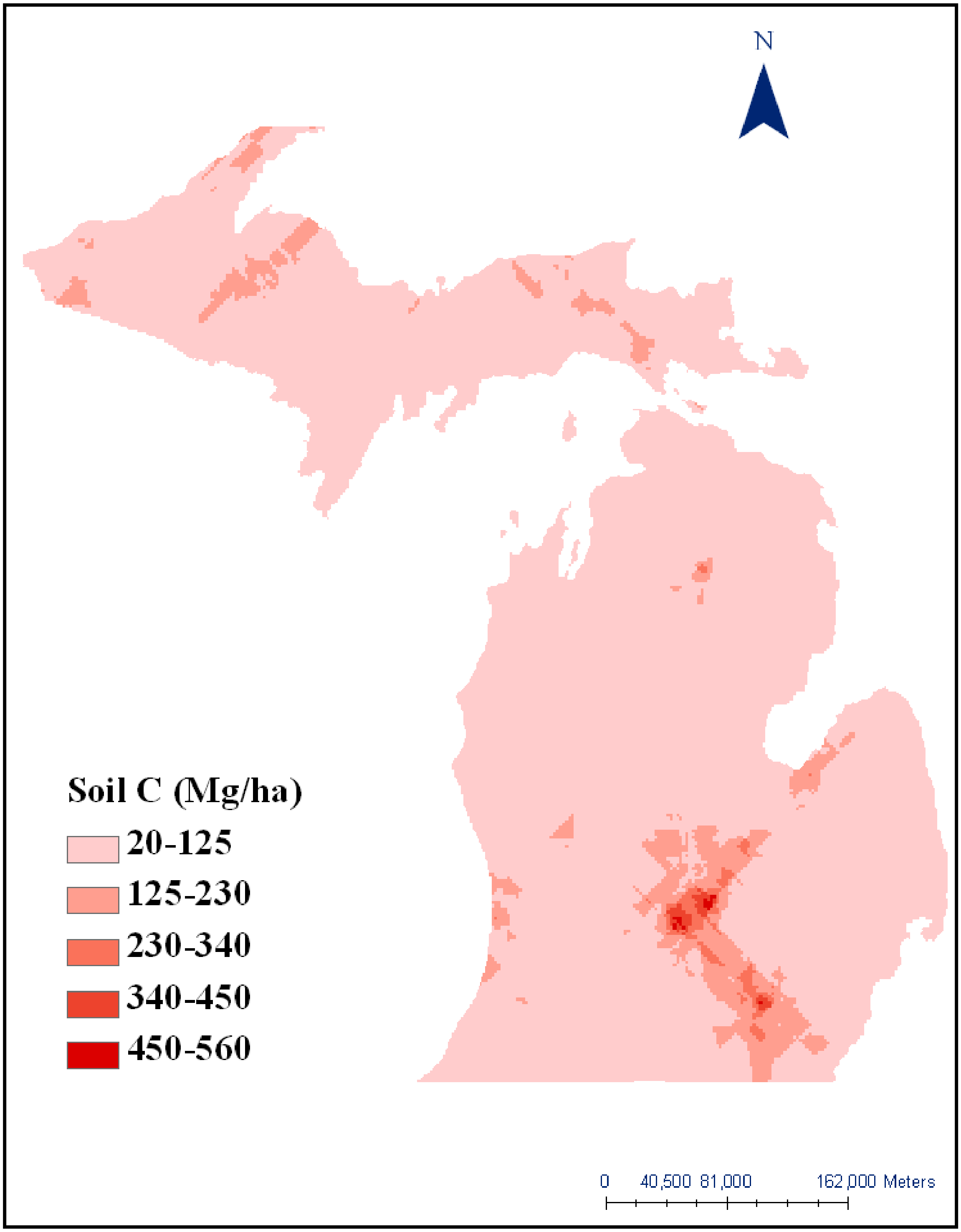

Figure 44. Predicted SOC Distribution for Michigan Soils up to 1.0 m Depth (Source: Kumar and Lal, 2010)

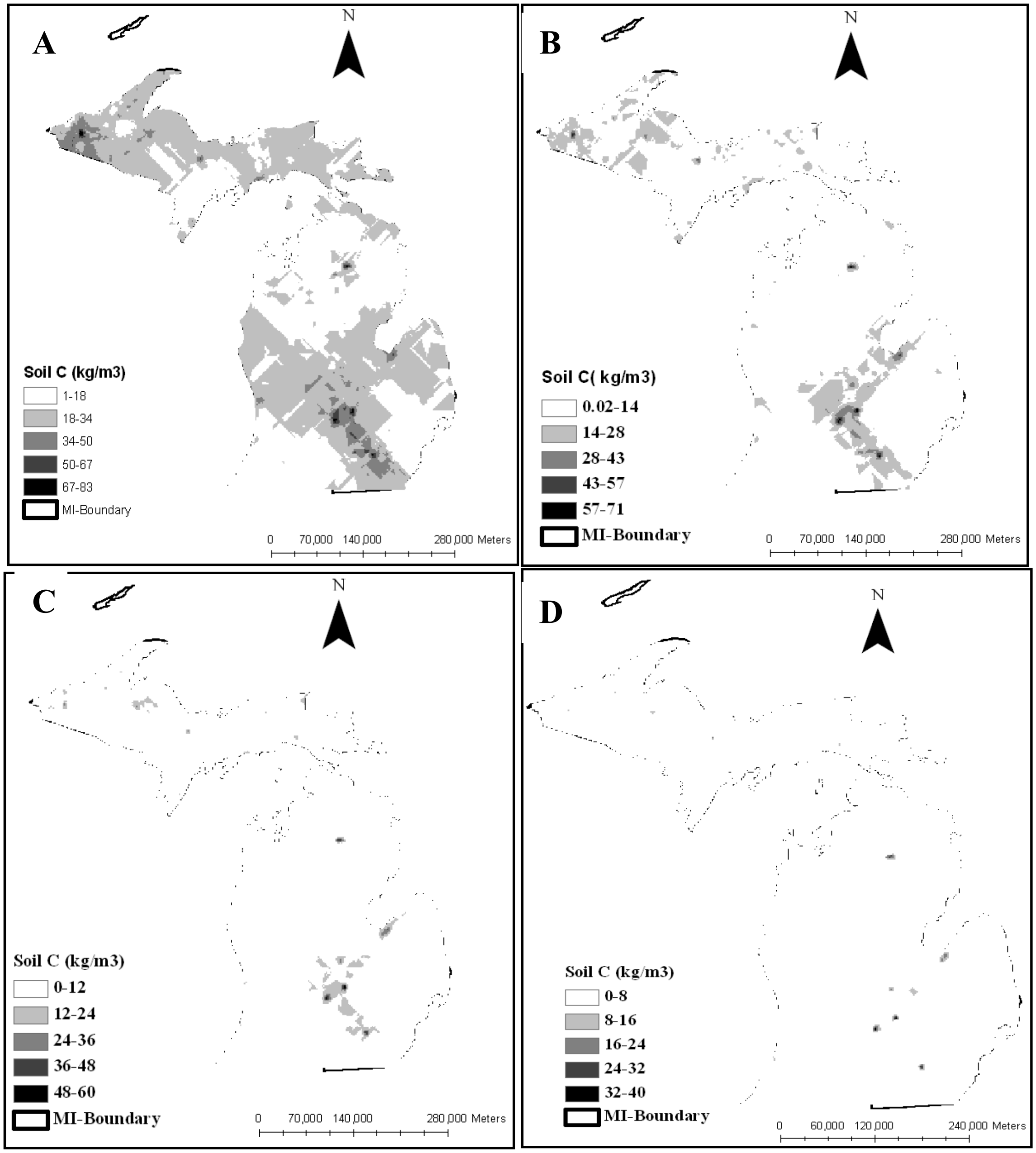

Figure 45. Distribution of the Soil Organic C (kg m^{-3}) at 0.15 (A), 0.30 (B), 0.50 (C) and 1.0 (D) Meter Soil Depth for Michigan

The SOC pool for Michigan ranged from 20-560 Mg/ha for 0-1.0 m depth. Higher C pool was present in MLRAs which was attributed to the presence of few Histosols and Mollisols . Higher SOC pool was estimated for the surface 0 to 0.15 m layer and beyond this depth the pool decreased to 1.0-m depth. For the studies conducted for Indiana by Mishra et al. (2009) and Kumar and Lal (2100) for Michigan OK methods and profile depth distribution function were used to estimate the SOC distribution with depth. The prediction method for estimating SOC pool for Ohio (Figure 46) and for Midwestern Region used were OK, MLR, RK and GWR approaches. GWR was the best prediction method compared to OK, RK and MLR methods for estimating the soil organic carbon pool at state and regional scale.

Mishra et al. (2010) estimated the SOC pool to 0-0.5 m depth for Midwestern region. The total SOC pool reported by these researchers was estimated to be 6.22 Pg (Figure 47). These researchers have reported GWR approach was the best approach to predict the C pool based on different environmental variables (e.g. temperature, precipitation, land use and bedrock geology). Based on the result, GWR can produce more accurate SOC maps than MLR, with similar or better accuracy than the RK approach. The total SOC pool in the 0- to 0.5-m depth was estimated to be 6.22 Pg. Considering the scale of the study and the availability of SOC observations, the GWR approach produced satisfactory accuracy in predicting the SOC pool. These researchers have proposed a simple methodology to predict the SOC pool at regional scales that can be used readily by land managers. In this context, GWR can play a vital role in improving the prediction ability of SOC pools across regional scales.

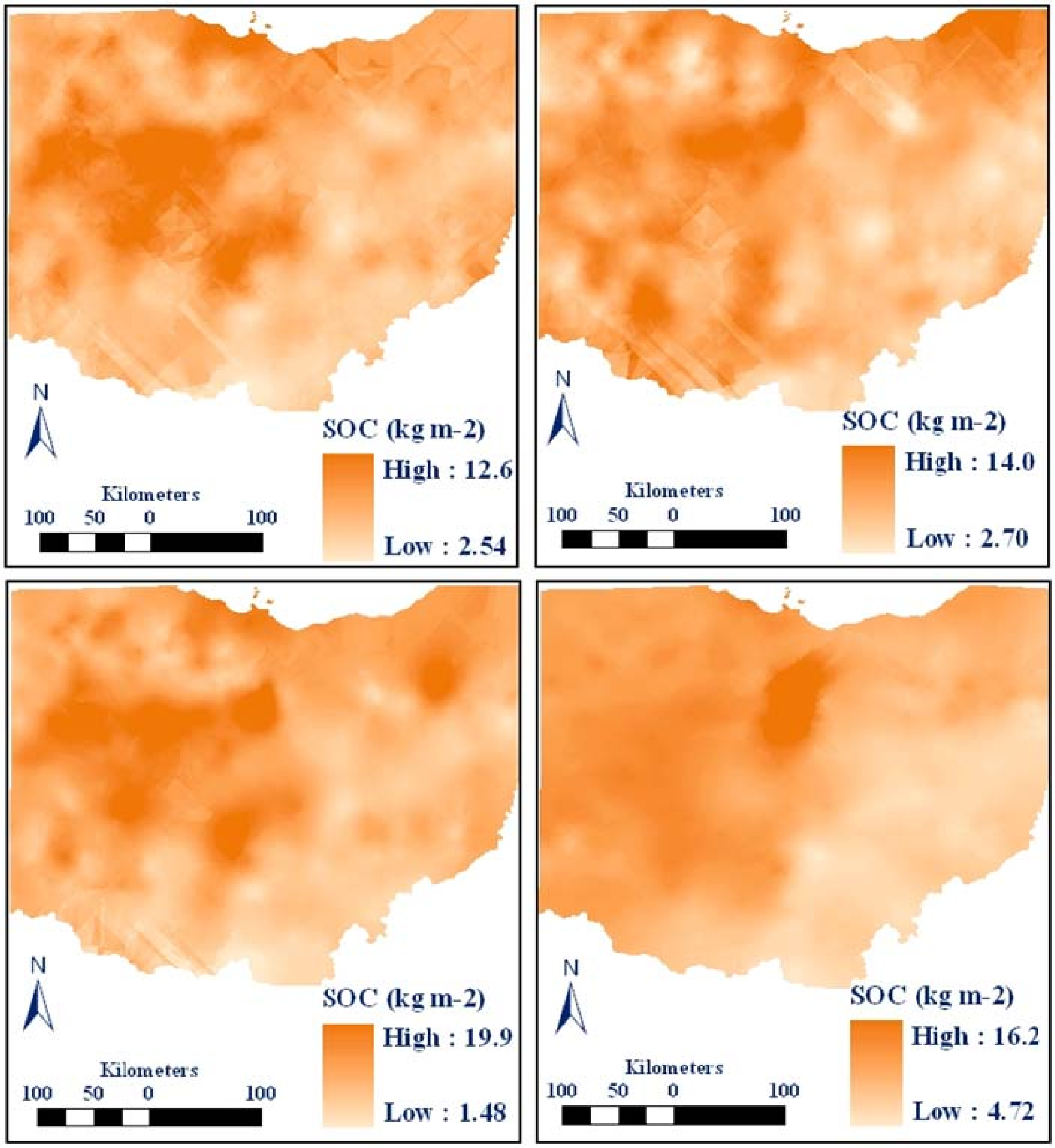

Figure 46. Estimated Soil Organic Carbon (SOC; kg m^{-2}) Density Maps for the Ohio State Using Ordinary Kriging (OK; top left), Multiple Linear Regression (MLR; top right), Regression Kriging (RK; bottom left), and Geographically Weighted Regression (GWR; bottom right) Approaches for Ohio

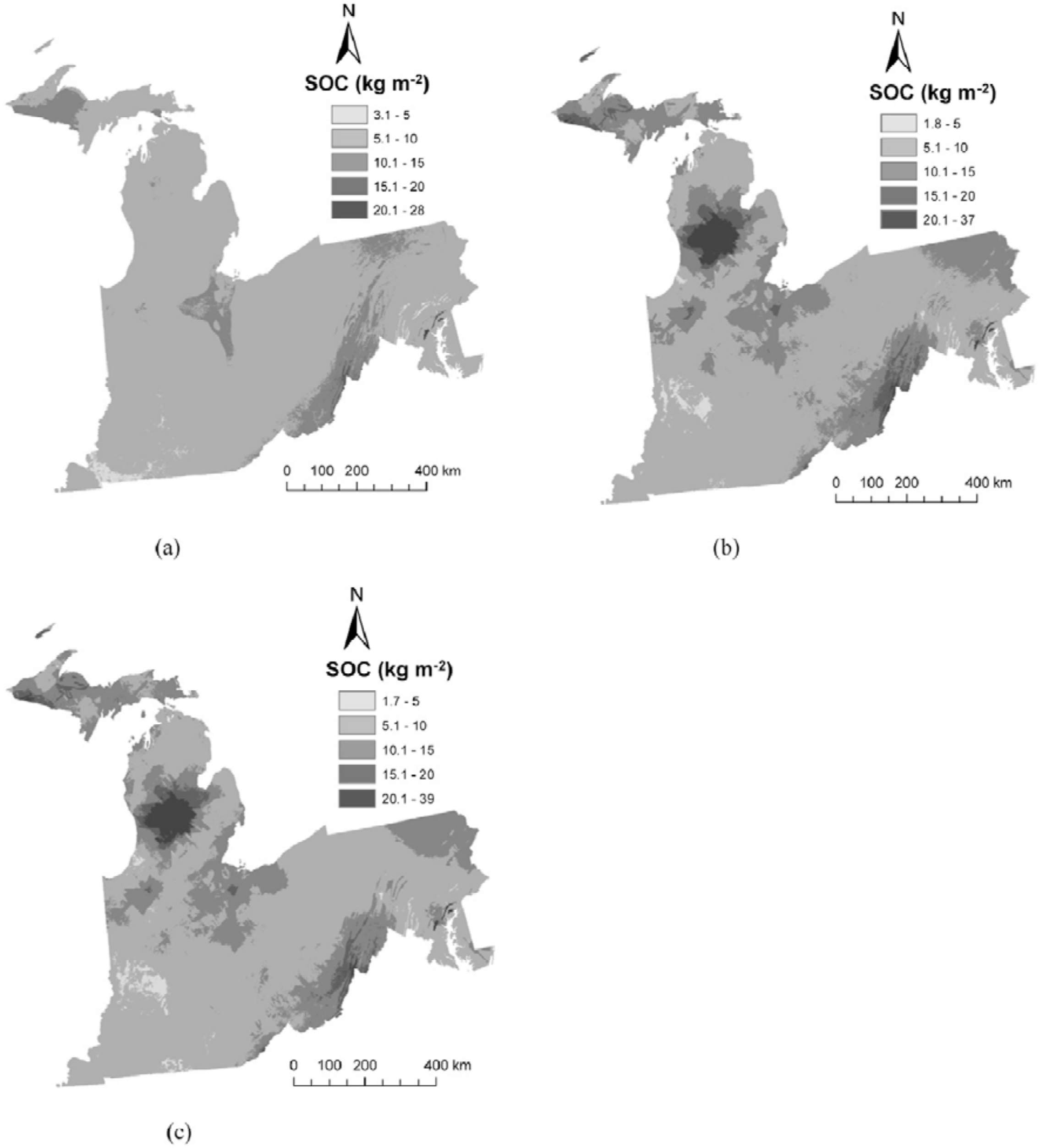

Figure 47. Predicted soil Organic C (SOC) Pool Maps for 0-0.50 Meter Soil Depth Using (a) Multiple Linear Regression, (b) Regression Kriging, and (c) Geographic Weighted Regression Technique for Midwestern Region (Source: Mishra et al., 2010)

12. FUTURE RESEARCH: BIOCHAR CARBON SEQUESTRATION IN AGROECOSYSTEMS

12.1 CMASC Future Research on Biochar

Recently, production of “biochar” has been proposed as a means of directly sequestering atmospheric C with ancillary benefits of replacing fossil fuel energy and, when incorporated into the soil, increasing crop productivity by 20% to 220%. Biochar is a highly porous, stable and C-rich byproduct of “pyrolysis,” an energy generation process wherein biomass is thermally decomposed at 300-700°C. When biochar is applied to soils, observed changes include increased CEC, decreased acidity, improved water retention capacity, reduced bulk density, and increased microbial an fungal activity. Biochar C sequestration values have been estimated at 0.14 to 3.5 Gt yr^{-1} by 2050 (2 to 42% of present annual anthropogenic C emissions from fossil fuels) (Figure 48).

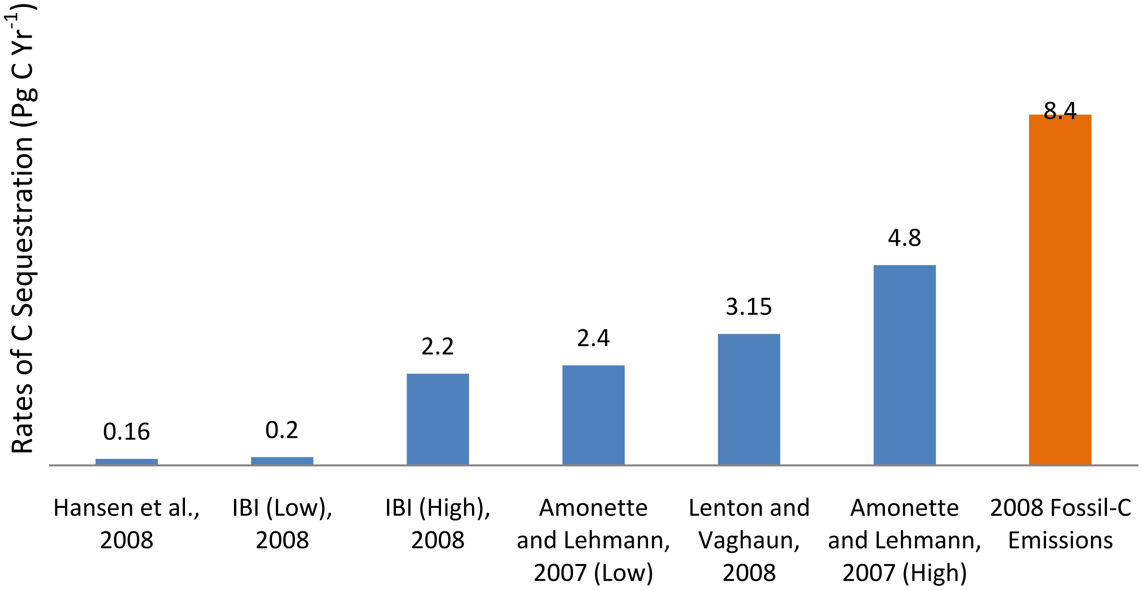

Figure 48. Estimates of Biochar C Sequestration Rates (Pg yr^{-1})
Source: Hottle, 2009 (unpublished)

Despite potential benefits of biochar, there remain significant research gaps that need to be addressed such as environmental impacts from appropriation of biomass, introduction of harmful substances into the soil, and increased mineralization of native C pools. Difficulty in analyzing these potential problems has arisen due to the high degree of heterogeneity of biochar types. The feasibility and necessary scaling of biochar to mitigate climate change by sequestering C in soil, substituting fossil fuel use by biomass pyrolysis, and reducing soil degradation depends on the outcomes of additional research.

When incorporated into soils, biochar has been observed to enhance soil quality and plant productivity while effectively sequestering atmospheric C for centennial to millennial time scales (Figure 49). These three benefits—for energy, soils, and climate—appear to offer a large lever for addressing multiple global challenges.

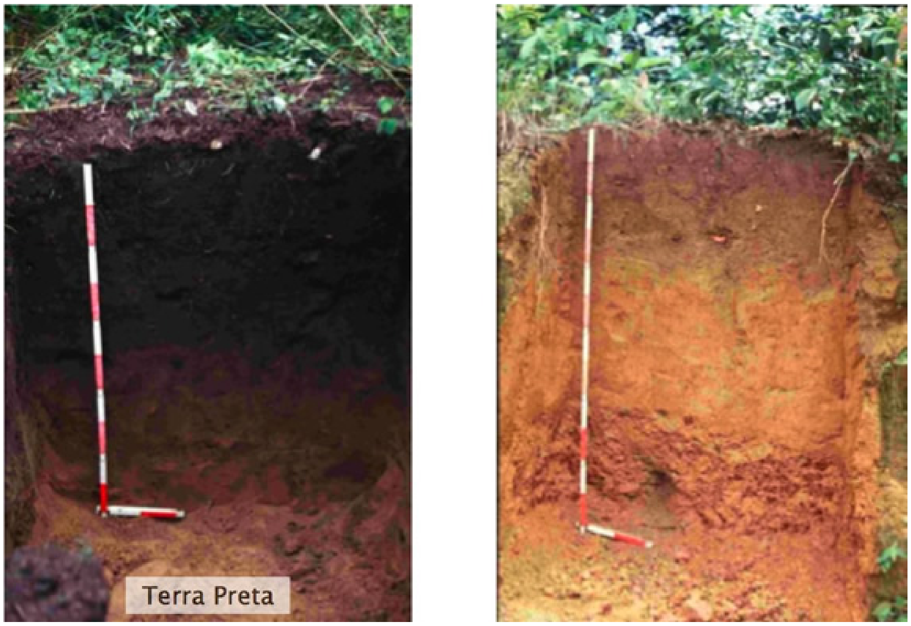

Figure 49. Comparison of Ancient "Terra Preta" Soils of the Amazon Which Have Been Amended with Biochar (left) and Neighboring Soils Without Biochar (right) (Source: International Biochar Initiative)

12.1.1 Objectives of Biochar Research. The objectives of this proposed research is to begin a long-term, large-scale interdisciplinary project that will comprehensively assess the entire lifecycle of biochar production and application as applied to the energy-agriculture-climate of soils characteristic of Midwestern U.S..

12.1.2 Experimental Approach. The proposed laboratory, field, engineering, and modeling research will be conducted in order to assess the potential of biochar production for carbon sequestration, increased crop productivity, and bioenergy generation.

This research involves long-term field trial (Figure 50) on approximately 1.5 hectare plot at The Ohio State University Waterman Research Farm located in Columbus, Ohio, 40° 00' 33.09" N, 83° 02' 29.16" W, with elevation of 242 meters within the Olentangy Watershed. Soil type of the said farm is Miamian (fine, mixed, active, mesic, Oxyaquic Hapludalfs), a representative soil type for much of the Midwestern U.S. The plot has been planted under a continuous maize (*Zea mays* L.) soybean (*Glycine max*) rotation for the past 6 years and is presently under maize production. Maize-soybean rotation will continue under biochar experiment.

Biochar is to be applied at four rates (0 megagrams per hectare [Mg ha^{-1}], 2 Mg ha^{-1}, 4 Mg ha^{-1}, and 8 Mg ha^{-1}) with three fertilization regimes (100% of standard fertility application and 80% of standard fertility application, and 60% of standard fertility application) and with three management practices (conventional tillage, no-till with incorporation, and no-till top dressing). The experimental design is to be a full factorial, split plot design. Thus, there will be 144 total plots of 8 m by 5 m, with 4 blocks each consisting of 36 plots.

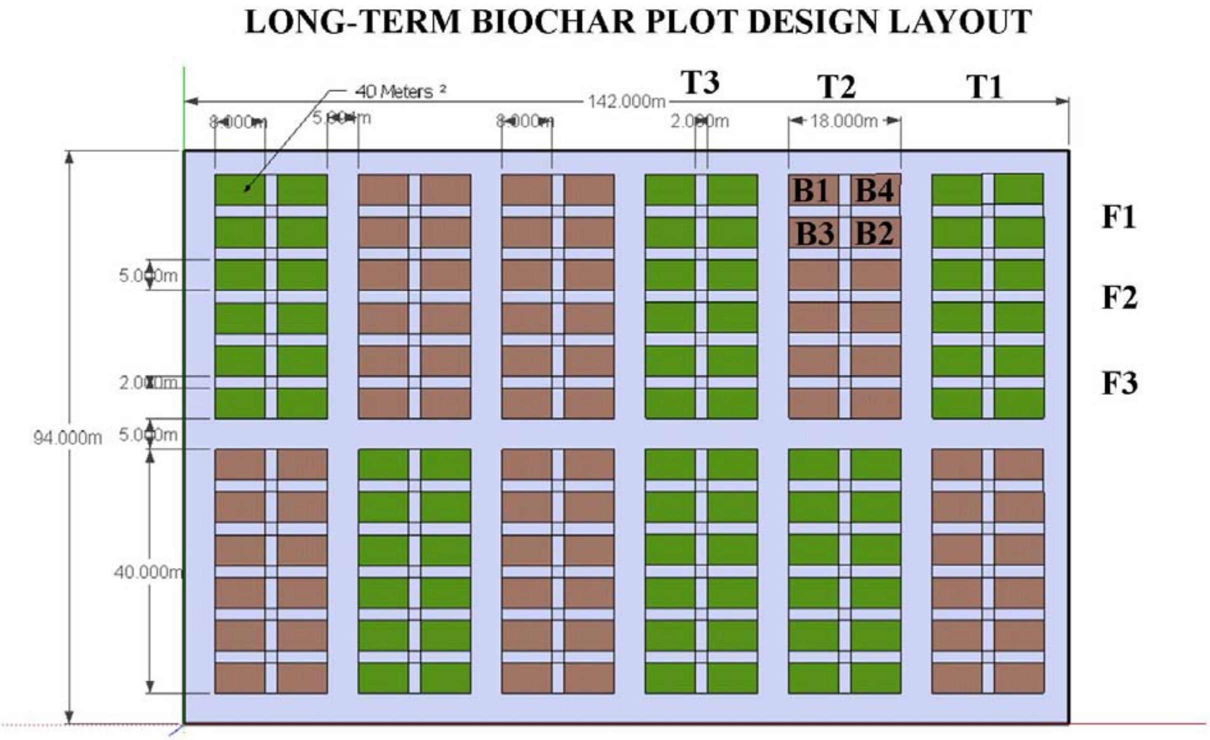

Figure 50. Layout of the Long-Term Biochar Experiment at the Waterman Farm, OSU, Columbus, Ohio (Source: Hottle and Eastman [2009] unpublished)

Measurements will be made for the soil and ecosystem C budgets, rate of C sequestration, emission of greenhouse gases, and biochar-induced changes in soil physical and chemical properties. Agronomic yields will be related to soil quality.

13. CONCLUSIONS

13.1. Programs & Opportunities

The Phase-II MRCSP studies on terrestrial carbon sequestration in cropland at OSU have resulted in the following:

1. ***Training Opportunities:*** The MRCSP created opportunities and supported research program of several graduate students. These included Umakant Mishra, Josh Beniston, Alexandria Horne, Ryan Hottle and Chris Eastman. Several postdoctoral researchers who conducted research and focused professional opportunities elsewhere include Sheila Christopher, Amitava Chatterjee, Humberto Blanco-Canqui, Zenghxi Tan, Rajith Mukundan, and Sandeep Kumar. Students presently working on the project are Ryan Hottle, Chris Eastman, and Josh Beniston. Postdoctoral researchers who worked on the project in 2010 are Ilan Stavi and Sandeep Kumar. Program manager supported partially through MRCSP included Brenda Swank, Pat Drillien, and Theresa Colson.

2. ***Research Findings:*** Principal research findings of Phase II include the following:

   (i) Residue retention as surface mulch is essential for soil carbon sequestration and soil quality improvement in no-till system.

   (ii) Rates of soil C sequestration, 250-1000 Kg C/ha/yr, depend on soil properties, crop rotations, residue management, soil fertility management, and the duration since conversion from plow tillage to no-till. Removal of surface residues for biofuels or other uses adversely impacts soil quality.

   (iii) Rather than assessment for the plow depth only, soil carbon pool in relation to land-use and management must be measured to 1-m or at least 0.5 m depth.

   (iv) Complete LCA of production system (i.e., no-till, plow tillage, manuring) must be conducted to assess management-induced changes in ecosystem carbon pool. The data on changes in ecosystem carbon pool are essential to developing an effective mechanism for trading carbon credits.

   (v) Residence time of carbon sequestered in soil depends on soil properties (more for clayey than sandy soils), depth (longer for sub-soil than surface soil), land use (longer for perennials than annuals), and management. The soil carbon pool is maintained or enhanced as long as no-till system and other BMPs are used.

   (vi) Soil quality is improved with increase in soil organic carbon pool, and increase in agronomic productivity is attributed to improvement in use efficiency of inputs (fertilizers) and decrease in losses (runoff, erosion, and mineralization).

   (vii) The soil carbon pool at regional scale can be reliably predicted by using GIS and terrain characteristics, and other modeling techniques. The up-scaling of soil C pool is extremely useful in assessing carbon credits for trading purposes.

(viii) Agricultural practices which sequester C in soil are those which create a positive C budget. This implies that C input into the system exceeds the C output (loss) by erosion mineralization and leaching. In this regard some farms under no-till in MRCSP did not enhance SOC pool compared with the plowed system.

3. ***Future Programs:*** Priority topics in future program include the following:

(i) Several projects initiated during the Phase-II must be continued for completion during the initial period of Phase-III and brought to fruition. Important among these are: (i) sampling of remaining soils in key MLRAs so that the data are complete, (ii) evaluation of other soil/crop management systems which create positive carbon budget (e.g., cover cropping, manuring), (iii) up scaling the data by simple techniques for the purpose of trading C credits, and (iv) prepare a manual for assessing soil carbon pool on regional basis for trading purposes.

(ii) Important and emerging technologies which have a tremendous promise and must be assessed within the MRCSP region include biochar application. Research data on biochar are needed for the rate and method of application, the technical potential of Csequestration, residence time, impact on soil quality, and agronomic productivity.

(iii) Additional information is needed on the complete life cycle analysis of promising production systems (e.g., no-till, biochar, manuring, cover cropping, residue removal for cellulosic ethanol) to assess the net changes in ecosystem C pool.

(iv) The information on net C gains (increase in ecosystem C pool) is needed for the production of bioethanol and other biofuels through detailed LCA of the entire process and with due consideration of all processes.

(v) A protocol must be developed for payment to farmers and land managers for ecosystem services including C sequestration.

(vi) In addition to CO_2, there is a strong need to also focus on other GHGs especially N_2O and CH_4 with GWP of 310 and 21, respectively.

(vii) Rather than just the cropland, the focus should also be on urban lands because of rapid urbanization.

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Appendix A

GLOSSARY OF TERMS

Aggregate size distribution: the average dispersal of various sizes of aggregates in a select soil sample

Agriculture horizon: a layer of soil approximately parallel to the land surface and differing from adjacent layers in physical, chemical, and biological properties such as texture, structure, consistency, color, and degree of acidity or alkalinity

Best management practices (BMP): practices recognized to be effective for soil conservation purposes that also provide water quality benefits

C:N ratio: ratio of Carbon to Nitrogen in a select soil sample

Carbon sequestration: biological or physical process that captures carbon dioxide and converts it into inert, long-lived carbon-containing materials

Cation exchange capacity: the amount of negative charge on soil (C mol + Kg^{-1})

Conservation tillage: any combination of tillage and planting practices that generally reduces the loss of soil and water relative to losses with conventional tillage

Conventional/plow tillage: the combination of primary and secondary tillage operations normally used for seedbed preparation and growing-season weed control for a given crop in a given region

Cumulative infiltration: the total water that enters a soil and has a direct influence on erosion

Eroded and no-eroded soils: soils in which the surface layer has been truncated by wind or water erosion are eroded. Those in which the surface layer is intact are no-eroded

Geographically weighted regression: The GWR approach includes a range of relationships among different variables (environmental, climatic and categorical variables) and SOC, and is a local spatial analysis. This is an advanced and recent approach for modeling spatially heterogeneous processes (Fotheringham et al., 2002). The GWR procedure used for the present study is: $\hat{C}(s_i) = \hat{\beta}_0(s_i) + \hat{\beta}_1(s_i)X_1(s_i) + \hat{\beta}_2(s_i)X_2(s_i) + \hat{\beta}_3(s_i)X_3(s_i) + \hat{\beta}_k(s_i)X_k(s_i)$ where $\hat{C}(s_i)$ is the predicted SOC density at the *i*th location, s_i are the co-ordinates for the *i*th location, $\hat{\beta}_0$

through $\hat{\beta}_k$ are regression coefficients, $X_1(s_i)$ to $X_k(s_i)$ are the environmental variables at the ith location, and k is the number of environmental variables

Geospatial analysis: referring to a particular location which is relative to the Earth's surface

Green house gasses (GHGs): heat-trapping gas such as carbon dioxide, methane, nitrous oxide, or dimethyl sulfide released into the atmosphere as a result of human activities (primarily fossil fuel combustion) and natural processes (e.g., cellular respiration, biomass decomposition, volcanic activity)

Hydrology: the study of water and its effects on soil quality, health, and erosion

Kokomo soil series: very deep, very poorly drained soils that formed in loamy materials overlying till. The Kokomo soils are in depressions on till plains

Major land resource areas: regions with similar soil, climate, vegetation, and physiography

Mean weight diameter: weighted average diameter of structural aggregates

Mulch tillage: the practice of preparing land for a crop in such a way that plant residues or other materials remain on the surface to provide protection against erosion by water and wind and to improve water conservation during the interval between crops and at least partly into the growing period of the next crop

Multiple linear regression: regression model which was used globally for the data set is mentioned as below $\hat{C}(s_i) = \hat{\beta}_0(s_i) + \hat{\beta}_1 X_1(s_i) + \hat{\beta}_2 X_2(s_i) + \hat{\beta}_3 X_3(s_i) + \cdots + \hat{\beta}_n X_n(s_i)$ where $\hat{C}(s_i)$ is the dependable variable (SOC, kg m^{-2}) at the ith location, β_1 through β_n are the regression coefficients, and X_1 through X_n are the explanatory variables

No-tillage: the practice of planting a crop without any tillage for seedbed preparation following the harvest of the previous crop

Ordinary kriging: used to estimate the value of a random variable at one or more unmeasured points

Organic tillage: using a cover crop and organic amendments to suppress weeds and create a sod through which crops can be planted

Paddock: an enclosed area used especially for pasturing or exercising animals

Peat soils: organic soils in which plant residues can be recognized

Pore size distribution: the average dispersal of spaces of different diameters between aggregates in a select soil sample

Reduced tillage: the total number of operations used to prepare a soil for a crop is reduced from that normally used under the prevailing soil and field conditions

Regression kriging: SOC at an unsampled location (s_0) is predicted by summing the predicted drift and the residuals (Odeh et al., 1994). The residuals from the regression were kriged to the prediction grid using the isotropic variogram model parameters and the kriged residual map was added to the regression predicted map for obtaining RK prediction map. The regression equation was generated by performing regression analysis between predictor variables and SOC density. The equation used to perform RK is given: $\hat{C}_{RK}(s_0) = \hat{C}(s_0) + \hat{\varepsilon}(s_0)$ where $\hat{C}_{RK}$ is the predicted SOC density using RK approach, $\hat{C}$ is the drift fitted using linear regression analysis, and $\hat{\varepsilon}$ are the residual values

Rotational grazing: allowing grazing on a given area for a relatively short time, then allowing grazing on a successive area also for a short time before again allowing grazing on the fist area

Rotational tillage: It involves use of plow/chisel tillage one year and that of no-till every other year

Runoff: portion of precipitation or irrigation water that does not infiltrate soils and flows across the soil surface into channels or streams

Saturated hydraulic conductivity: it is the rate of transmission of water through saturated soil under a known hydraulic head gradient

SOCP: soil organic carbon pool

Soil Erodibility: the ability and likelihood of soil to be eroded by any means: wind, water, tillage, etc

Soil erosion: any process by which soil is removed from a specific plot of land and cannot be returned to it

Soil health: the ability of the soil to supply adequate nutrients in proper balance to plants

Soil inorganic carbon: it refers to mineral carbon in soil in the form of carbonates and bicarbonates

Soil organic carbon: carbon in soils that is a result of organic matter decomposition

Soil organic carbon pool/stock: the amount of C stock in the soil to a known depth

Soil penetration resistance: soil's ability to prevent water, air, and plant roots penetrating or passing through the bulk mass or specific layers of a soil

Soil quality: combination of all soil factors including aggregate stability, health, management practice influence, carbon levels, and texture

Soil texture: the relative proportions of the different soil separates (sand, silt, and clay) in the soil mass

Soil water retention: the amount of water, minus the antecedent water content, that remains in the soil and does not runoff

Sorptivity: measure of the capacity of the soil to absorb or desorb liquid by capillarity

Surface interpolation methods: The methods make predictions or estimations from sample measurements (e.g. soil carbon) for all locations of an area. There are ranges of methods to derive a prediction for each location. Few commonly used are inverse distance weight, ordinary kriging, regression kriging, and geographically weighted regression methods. Only certain methods are applicable for specific data

Tensile strength: maximum strength an aggregate can withstand before losing stability

Transmissivity: ability of soil to transmit water from one layer to another. With long-term, transmissivity approaches saturated hydraulic conductivity

Water infiltration rate: rate at which water will penetrate the soil surface, impacted by aggregates and surface sealing

Water stable aggregates: aggregates that do no disintegrate when wet

Woodlots (forest land): lands used primarily for growing trees or shrubs; including forests, shelter belts, windbreaks, hedgerows, and tree-covered stream banks

Appendix B

LABORATORY PROCEDURES OF ENVIRONMENTAL SOIL PHYSICS

CONTENTS

Page

INTRODUCTION

OBJECTIVES

The objective of the soil physics laboratory is to provide practical training in measurement of soil physical, mechanical, and hydrological properties. These laboratory experiments constitute an important component of soil physical analysis to complement the field (*in situ)* measurements of properties. While field measurements are obviously preferable, constraints such as techniques, logistics, and weather conditions do not always permit field measurements. Laboratory experiments offer a valuable opportunity to learn the theoretical background and provide hands-on experience in conducting practicals. They are designed to conduct experiments, analyze and interpret the data, and report the results in a concise, clear, and timely manner as part of the learning experience.

Laboratory practices are primarily intended to acquaint students with the techniques and approaches of determination of soil physical characteristics. They are a vital approach to complement and advance the understanding of the theoretical concepts discussed during the lectures. Finally, these practicals are to equip students with laboratory skills to conduct their own and independent research projects in the near future.

A. Modus Operandi

1. Each student will be provided with soil samples for conducting laboratory experiments.
2. In the first practical, each student will prepare his/her soil samples for the upcoming experiments.
3. The same sample will be used for all practicals throughout the course.
4. Each student is expected to:
    - 4.1 Study the corresponding practical for each session in advance.
    - 4.2 Conduct an independent experiment and record data and results.
    - 4.3 Maintain and leave his/her laboratory area in a neat and orderly manner to adhere to lab protocols.

B. Demonstration

In addition to “hands on” practicals, the laboratory instructor will demonstrate several other techniques of characterizing soil physical, mechanical, and hydrological properties.

C. Safety

According to the new safety regulations of the University, each student must wear protective goggles and shoes so long as he/she is inside the lab. Goggles will be provided by the soil physics lab.

D. Reports

Each student will prepare an independent report for each of the practical exercises, which will be due one week after the completion of the experiment. The report should conform to the following guidelines:

1. Number and title of experiment, course name, student’s name, and date.
2. Introduction.
3. Objectives.
4. Materials and methods (includes the description of the procedures, equipment used, and mathematical equations).
5. Results (includes reporting of data in tables and figures and basic data analysis).
6. Discussion (brief interpretation of the results, explanation of possible reasons for the outcomes, and discussion of potential shortcomings and significance of the practice).
7. Conclusion (a short summary of the evidence).
8. References

Reports should by typed or written legibly on 8 ½” by 11” paper.

E. Literature Review

Students are expected to cite relevant and new literature in support of the arguments for each lab report. They are strongly encouraged to read topics related to each experiment from current journal articles in soil science to become familiar with the study subject and acquainted with styles of publications including introduction, objectives, presentation of results, write-up of discussions, and literature citations. Some literature references are provided at the end of each practical.

F. Interpretative Summary

Each student, at the end of the quarter, will provide a concise summary of the interpretation of results obtained indicating potentials and restraints of the assigned soil in terms of water availability, root growth, water movement, drainage, aeration, and susceptibility to crusting, compaction and erosion. This report is due before the final examination. The format for this report should be the same as outlined previously for the weekly reports. Since all experiments will be conducted on the same soil samples, the student is expected to integrate and draw conclusions based on the data.

The final report should include an integrated discussion on laboratory practicals conducted during the quarter. Emphasis should be on the inter-relationships among soil physical properties: i) particle size distribution, plasticity, shrinkage characteristics, and soil wetness; (ii) texture, particle density, bulk density, aggregation, aggregate strength, and compactability; (iii) texture, soil water retention curves, pore size distribution, and plant-available water reserves; and (iv) texture, structure, infiltration rate hydraulic conductivity, soil drainage and erosion.

Practical 1A: Soil sample preparation

The steps for the preparation of soil samples are the following:

1. Collect and air-dry about 2000 g of bulk soil samples from different soils.
2. Break up large clods with a rolling pin or rubber mallet and sieve out at least 100 g of aggregates between 5- and 8-mm sizes for each soil.
3. Store these aggregates in previously labeled plastic bags (sample number and student's name).
4. Pass the remaining soil through the rollers of the grinding machine a little at a time to avoid jamming the machine.
5. Sieve the ground soil through a 2 mm mesh and store in plastic bags.
6. Grind enough soil to obtain about 1 kg of sieved soil sample for the particle size analysis, particle density and infiltration rates.
7. Store the soil samples in drawers assigned for your use.
8. Obtain two soil cores from the instructor for the determination of bulk density, soil water characteristics, saturated hydraulic conductivity, and air permeability experiments. Store these cores in plastic wrap in the refrigerator.

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Practical 1B: Soil water content and bulk density

INTRODUCTION

The water content of the soil is a key factor controlling plant growth, air flow, compaction, soil temperature, microbial processes, and other physical and mechanical soil processes. It is closely related to the bulk density (ρ_b) of soil as it affects dynamically the total volume of the soil. The simplest and most conventional technique to determine the water content of a soil sample is the gravimetric approach. The determination of the gravimetric water content (w) of the soil is usually a companion measurement to soil bulk density. “The product of w and ρ_b divide by the density of water (ρ_w) gives the volumetric water content (θ), which refers to the volume of water per unit of total soil volume.

The ρ_b is a measure of the oven-dry (105°C) mass of dry solids per unit total volume of the soil. The ρ_b is an essential input to compute the θ, porosity, and total mass of the soil. As with water content, the ρ_b is a dynamic soil property, varying spatially and temporally. Several techniques exist for the determination of soil bulk density including core, clod, radiation, and excavation methods, which are discussed below. All these methods require the determination of the oven-dry mass of the soil.

The objectives of this experiment are to: 1) determine the gravimetric water content, 2) compute the bulk density of the soil, and 3) calculate the volumetric water content.

Equipment and materials

- Soil cores, cans, thread or thin string, fume hood, knife, plastic bags, balance, oven, scissors, and rubber mallet.

Procedure

The assigned two soil cores will be used for the determinations of gravimetric water content and ρ_b as follows:

Water Content

1. Label and weigh two empty and clean cans.

2. Trim carefully both ends of each soil core flush with the open ends of the rings using a serrated knife while avoiding any soil smearing.
3. Place a portion of soil trimmings into the empty water cans and weigh the cans + moist soil.
4. Dry the cans + moist soil in an oven at 105°C for 24 h.
5. Record your name and the shelf number on the sign-up sheet on the oven door.
6. Remove the cans + dry soil from the oven after 24 h, let them equilibrate with the room temperature, and then weigh them.
7. Compute the w (g g^{-1}) as follows:

   Tin mass (M_1)

   Tin + moist soil mass (M_2)

   Tin + dry soil mass (M_3)

   $w = (M_2 - M_3) / (M_3 - M_1)$
8. Compute θ ($mm^3\ mm^{-3}$):

   $\theta = w * \rho_b / \rho_w$

   where ρ_w, the density of water, is obtained from the Handbook of Chemistry and Physics. The ρ_w at 25°C is about 1 g cm^{-1}.

Bulk Density

Core Method

1. Trim both ends of the soil core flush with the rings using a serrated knife.
2. Use scissors to cut any roots sticking out the ends of the soil cores.
3. Obtain and record the mass of the trimmed soil cores.
4. Obtain the mass of empty metal cores from the instructor.

Other Methods

Clod Method

The clod method us useful to determine the bulk density of clods, or coarse peds, based on their mass and volume. The volume is determined by coating a clod of known mass with a water-repellent substance (such as saran, paraffin, wax) and by weighing it first in air, then again while immersed in a liquid of known density, making use of Archimedes' principle. The clod or ped must be sufficiently stable to cohere during coating, weighing and handling.

Procedure

Secure the clod with two loops of thread or wire, loops being at right angles to one another, leaving sufficient thread or wire to connect the balance arm. Weigh the clod and thread. Holding it by the thread, dip the clod into the saran solution. Suspend it in air under a hood for 15 to 30 minutes to allow the solvent to evaporate. Repeat dipping and drying one or more times as needed, to waterproof the clod. Weigh the clod, with its coating and the thread. Weigh it again when it is suspended in water and note the water temperature. Determine the tare mass of the thread or wire. To obtain a correction for water content of the soil, break open the clod, remove an aliquot of soil, and weigh the aliquot before and after oven-drying it at 105°C.

Calculate the oven-dry mass of the soil sample (M_{ods}) as follows, from the water content of the aliquot removed from the clod after the other weights are taken:

$$M_{ods} = M_{sa} / (1 + w)$$

Where M_{sa} = Mass of clod or ped in air at its original water content. Calculate bulk density as follows:

$$\rho_b = \rho_w M_{ods} / [M_{sa} – M_{spq} + M_{pa} – (M_{pa}\rho_w / \rho_p)]$$

where

ρ_w = density of water at temperature of determination,

M_{ods} = oven-dry mass of soil sample (clod or ped),

M_{sa} = mass of clod or ped in air,

M_{spw} = mass of soil sample plus saran in water,

M_{pa} = mass of saran coating in air, and

ρ_b = density of saran.

Radiation Methods

The transmission of gamma radiation through soil or scattering within soil varies with soil properties, including bulk density. By suitable calibration, measurements of either transmission or scattering of gamma radiation can be used to estimate bulk density.

In the transmission technique, two probes at a fixed spacing are lowered into previously prepared openings in the soil. One probe contains a Geiger tube, which detects the radiation transmitted through the soil from the—gamma source located in the second probe. The scattering technique employs a single probe containing both gamma source and detector separated by shielding in the probe. It can be used either at the soil surface or placed in a hole, depending on the design of the equipment. Radiation methods have several advantages, among which are minimum disturbance of the soil, short time required for sampling, accessibility to subsoil measurements with minimum excavation, and the possibility of continuous or repeated measurements at the same point. Both transmission and scattering techniques measure the bulk density of all components combined. The densities of gaseous components are insignificant in comparison to those of solid or liquid components, and can therefore be ignored. It is necessary, however, to determine the water content of the soil at sampling time and to apply a correction to obtain bulk density on a dry soil basis.

Comments

There is some radiation hazard with these methods. Gamma photons are high-energy radiation and some can pass through several centimeters of lead shielding. Commercially available equipment reduces the hazard to safe levels. It is important to adhere strictly to time limits, distances and instructions described by the manufacturers. One should be equipped for and knowledgeable in means of checking equipment for radiation levels according to the way it is handled in actual sampling. If there is doubt, the equipment should be checked for safety by a competent testing laboratory.

Since radiation transmitted from a source to a detector is dependent on probe spacing or sample thickness, care must be exercised with the two-probe sampler to assure that access holes are parallel and spaced exactly as in the calibration.

Excavation Method

Bulk density is determined in this method by excavating a quantity of soil, drying and weighing it, and determining the volume of the excavation. In the sand-funnel method, the volume is determined by filling the hole with sand, of which the volume per unit mass is known. In the rubber-balloon method, the volume is determined by inserting a balloon into the excavation and filling it with water or other fluid until the excavation is just full. The volume of the excavated soil sample is then equal to the volume of the fluid dispensed. If the excavation is carefully done it is possible simply to measure its dimensions and calculate the volume.

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Practical 2: Particle Density of soils

Particle density (ρ_s) is an intrinsic property of soil as it is entirely dependent on the constituents composing the solid fraction. It is determined by the proportion of mineral and organic fractions and by the specific gravity of these constituents. Organic matter has a specific gravity in the range of 1.0 to 1.3 Mg/m^3, while the specific gravity of soil minerals ranges from 2.55 to 3.35 Mg/m^3. Most mineral soils have a particle density of about 2.70 Mg/m^3, which is an average density of both organic matter and inorganic soil particles. Soils with organic matter content tend to have lower values of ρ_s. Two picnometer techniques for the determination of ρ_s are discussed below although the electronic picnometer is not widely used.

A. Pycnometer Method

Apparatus and Supplies

1. Pycnometer of known volume.
2. Distilled or de-ionized water.
3. Vacuum pump.
4. Desiccator.
5. Thermometer (graduated to 0.1°C).
6. Pipette.
7. Beakers (2-3, 150 ml capacity).
8. Spatulas.
9. Aluminum dishes or cans.

Procedure

1. Weigh a clean, dry, and empty pycnometer including stopper (M_{empty}).
2. Weigh 7 g of air-dry soil, passed through a 2 mm sieve, to the nearest 0.01 g and transfer carefully into the pycnometer.
3. The soil sample must be corrected to oven-dry water content.
4. Weigh the pycnometer and soil (plus stopper) to the nearest 0.01 g and record the mass (M_s).

5. Add distilled water until the pycnometer is about half full, then add 3-5 drops of amyl alcohol to reduce foaming.
6. Place pycnometers and beaker with extra distilled water in a desiccator. Evacuate with a vacuum pump until air bubbling ceases (i.e., 0.07-0.1 MPa vacuum) for at least 15 min.
7. Removal of entrapped air can also be done by gentle boiling (about 5 min) and agitation of the contents.
8. Fill the pycnometer to the top with the de-aired distilled water.
9. Insert the stopper and dry the outside of the pycnometer and weigh to the nearest 0.01 g, recording the mass (M_{sw}).
10. Empty the contents and weigh the pycnometer when full of distilled water (M_w) and record the temperature of water.
11. Determine the density of water (ρ_w) at the temperature measured.
12. Weigh about 25 g of air-dry soil to the nearest 0.01 g to determine the water content of the soil.
13. Calculate particle density (specific gravity) as a ratio of mass of oven-dry mass of soil to the volume of the solids.

Results

Tabulate your results, reporting particle density values to three significant figures. Show each calculation in arriving at your experimental results.

Calculations

Particle density, ρ_s = Mass of soil / volume of soil = $(M_s' - M_{empty}) / Vs$

Experimental calculation of $\rho_s = \rho_w (M_s' - M_{empty}) / [(M_s' - M_{empty}) - (M_{sw} - M_w)]$

B. Electronic Pycnometer

The Multivolume Pycnometer 1305 allows the rapid determination of sample volumes.

Method for Electronic Pycnometer

a) Start up

For initial instrument operation or use after several days. Turn power on to illuminate pressure display. Open sample chamber and clean if necessary. Wipe upper rim and upper inside surface of chamber with a clean lint-free cloth/tissue to remove particles or great build-up from O-ring. Inspect bottom of sample chamber cap and clean the sealing plug and its flat surface. Make sure O-ring is undamaged and grease film is adequate.

Clean and install the desired sample chamber. Remove any insert present if the 150 cm^3 range is to be used. Removal of the sample inserts is best done by opening the VENT valve with the VENT RATE control opened several turns (CCW) and then opening the FILL valve to allow the gas to gently east the insert up until it can be grasped. Avoid forcing the insert out. Insertion of inserts is best accomplished with the VENT valve open and the VENT RATE control opened several turns (CCW). Make sure that the insert is properly aligned.

Close the fill valve if it was opened. Place the PREP, TEST valve (Figure 3.1) in the TEST position; the >5, <5 valve in the >5 position; and the >35, <35 valve in the >35 position; open the VENT valve. Remove the sample cup from the chamber and replace the sample chamber cap. Open the FILL valve and allow the gas to flow through the instrument for about 5 min. Use a mid-range setting on both flow-rate control valves.

Close the FILL valve and wait until the pressure reading falls and stabilizes. Adjust the ZERO control to indicate ± 0.000. Rotate the >5, <5 and >35, <35 valves to the desired range positions. Turn the PREP, TEST valve to the PREP position. The instrument is now ready to run samples.

b) Sample preparation and weighing

Sample preparation consists of 1) removing any vapors in the sample (esp. water) which would interfere with the pressure ratios measured by the instrument; and 2) placing it in a sample cup of appropriate size. Weighing the sample is required if density or specific volume is to be computed. Weighing is best done after vapor removal and after running the sample. Weighing and recording the weights of the empty sample cups will permit the net mass of the filled sample cups to be calculated later. Porous samples which trap helium may cause buoyancy and mass drift so care should be exercised to purge the samples thoroughly with dry air or nitrogen if the highest degree of accuracy is required.

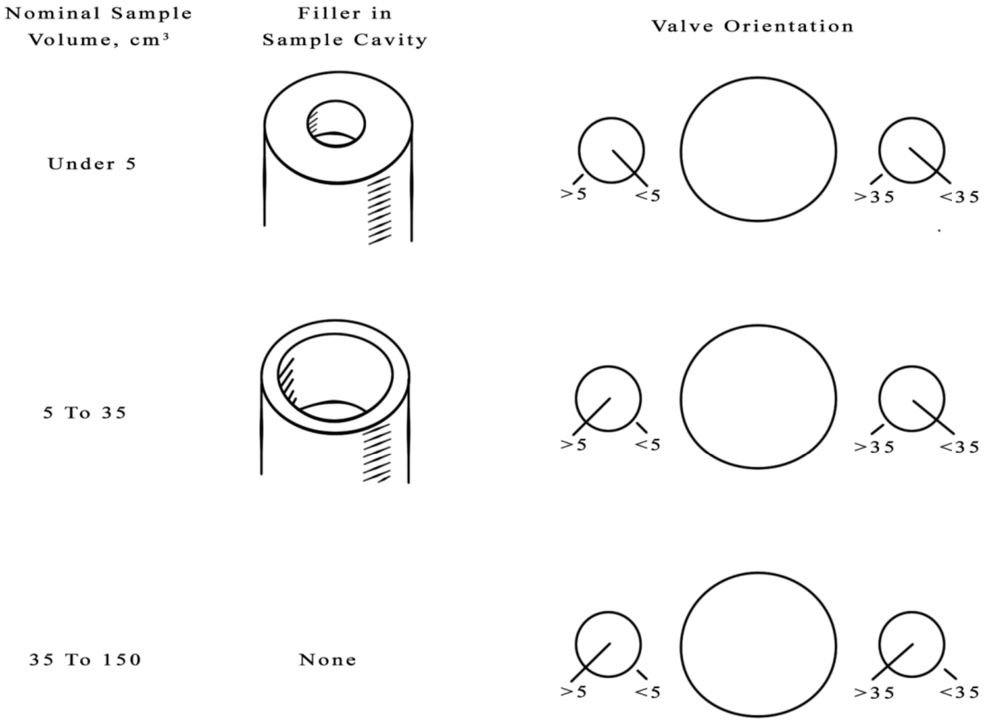

Figure 11.1 Setting the Multivolume Pycnometer for optimum results according to sample volume.

c) Running the sample

After setting ranges and filled sample cup inserted the following procedure:

1. Close the FILL valve if not already closed.
2. Turn the PREP, TEST valve to the PREP position.
3. Open the VENT valve if not already open.
4. Remove the sample chamber cap.
5. Remove any previous sample and/or insert and cup.

6. Insert the new sample and/or insert.
7. Securely place the sample chamber cap.
8. If sample is a light powder, close the FILL RATE and VENT RATE valves.
9. Open the FILL valve and gently increase the flow rate by opening the FILL RATE and VENT RATE valves to about mid-range if the sample is a light powder.
10. Air and vapors trapped within pores and crevices will be removed from the sample by a prolonged purse in this condition. However, these gases are more rapidly removed by alternately increasing and decreasing the gas pressure in the sample chamber. Close the VENT valve and allow the pressure to rise.
11. When the indicated pressure has risen to 16-18 psi, close the FILL valve and open the VENT valve. When pressure drops to 0.5-1 psi, close the VENT valve and open the FILL valve. Repeat 8-10 times for powdered or porous samples.
12. Close the FILL valve and let the VENT valve open.
13. Turn the PREP, TEST valve to the TEST position.
14. Allow the pressure to fall to zero and stabilize, adjusting the ZERO control as necessary.
15. Turn PREP, TEST valve to the PREP position ensuring that the zero does not shift. If a shift occurs, return the valve to TEST and repeat Step 14.
16. Close VENT valve neglecting any change of pressure.
17. Open FILL valve and fill the chamber to 19.5 ± 0.200 psi.
18. Close the FILL valve and allow pressure to equilibrate for 15-30 sec, recording it as P_1.
19. Immediately turn PREP, TEST valve to TEST and allow pressure to equilibrate, recording it as P_2.
20. Open the VENT valve. First close the VENT RATE control if light powders are being run and gradually open it as the pressure approaches zero.
21. Return to Step 14 if multiple determinations are to be made on the sample.
22. Remove the sample and cup using the bent-end probe provided in the accessory kit. Hook the probe in the hole in the upper lip of the cup and pull upward until the cup can be grasped with fingers.

23. If a new sample is to be analyzed, return to section (b) and repeat procedure. If the instrument is to remain idle for several days or more, close the sample chamber and shut off the helium supply.

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Practical 3: Particle size determination

INTRODUCTION

The size of soil particles known as soil texture is the most important property used for evaluation the physical attributes of a soil. Sand (50-2000 µm), silt (50-2 µm), and clay (<2 µm) are three particle size fractions that define the textural class of a given soil. The size of particles is a critical soil physical property controlling the physical, mechanical, hydrological, thermal, chemical, and biological processes. It governs the dynamics of water and air movement, erosion, organic matter decomposition, shrink-swell potential, etc. The analysis of particle size consists of measuring the size distribution of individual particles and reporting the results in percentages of sand, silt, and clay or a given soil sample.

A number of techniques are available to quantify the particles size distribution including sieving and sedimentation procedures, optical and scanning electron microscopy, laser light scattering, and x-ray centrifuges. The two commonly used standard procedures include the hydrometer and pipette methods. A simple and rapid field approach to estimate the textural characteristics of a soil is the “feel” method, which consists of rubbing a moist soil sample between the thumb and the index fingers while feeling the grittiness and smoothness of the mixture.

Techniques of determination

Hydrometer Method

The hydrometer method is more widely used for mechanical analyses of soil than any other method. It is in general use in Highway Department Soil Testing Laboratories in the USA. The method is simple and rapid, and it can even be used in the field for “on the spot” determinations of texture when high accuracy is not needed. The pipette method provides more accurate results than the hydrometer method.

The hydrometer method was developed as an empirical procedure for relating the density of a soil suspension with its particle-size distribution. The density is estimated with a specially shaped hydrometer which operates in principle like one used to measure the density of storage battery fluid, or the density of any other fluids (e.g., milk). Since particles of different sizes also settle at different velocities, it is possible to correlate the amount of various-sized particles in suspension by recording the hydrometer reading at appropriate settling times. The procedure was developed for a silt loam soil, and consequently, is usually more accurate when used with medium textured soils.

In this experiment, the objective are: (1) to obtain experience in determining sand, silt and clay contents by the hydrometer method, and (2) to use the textural triangle to determine the textural classes from data of several soils supplied by the instructor. Hydrometer analyses on all soils are to be run in duplicate. If the discrepancy in sand, silt, or clay contents between duplicates exceeds 5%, additional analyses are to be done on the sample until satisfactory results are obtained.

Materials

1. Multimix machine with baffled "milkshake" cups.
2. One-liter cylinders for containing soil suspension during settling.
3. Hydrometers for measuring density of soil suspension.
4. Thermometers for measuring the temperature of the suspension.
5. Sodium Hexametaphosphate dispersing agent.
6. A 300-mesh sieve.
7. Constant temperature water bath (optional).

Procedure

Weigh 51.0 g of air-dry soil which has been passed through a 2-mm sieve and transfer to a "milkshake" mix cup (51.0 g air-dry soil represents approximately 50.0 g oven-dry soil). If the soil is estimated to contain 75% or more sand, 101.0 g of soil should be used. Add 50 ml of 0.2N Na-hexametaphosphate (HMP) and about 75 ml of deionized water. Mix with a stirring rod and let the sample set for 30 minutes.

Stir the soil suspension for 15 minutes with the multimix machine. Then transfer the suspension from the cup to the settling cylinder. Add deionized water to the lower mark. The volume will then read 1000 ml.

Cover the top of cylinder tightly with the palm of the hand, and invert several times until all soil is in suspension. Alternatively, a special stirring rod may be used to prepare a uniform suspension. Place cylinder on flat surface and note the time. Immediately place hydrometer into suspension, sliding it in slowly to avoid bounding, until it is floating. Take the first reading on the hydrometer at 40 seconds from the time the cylinder was set down. Remove hydrometer and record the temperature of the suspension. Use three to four drops of alcohol in case of foam at suspension-air interface.

Take a second hydrometer reading at 3 hours along with a second temperature reading. The first reading provides a measure of the percentage of silt and the second clay in suspension. The second reading indicates the percentage of 2 μm (micrometer = 10^{-6} m) clay in suspension.

Readings are corrected to a temperature of 20°C or 68°F. For each degree over 68°F, add 0.2 to the reading before computation, and for each degree under 68°F, subtract 0.2 from hydrometer reading (see calculation). Avoid temperature extremes such as 50°F and 100°F.

A check (or substitute) for the 40 sec. reading can be made by sieving the entire suspension through a 300 mesh sieve to obtain sand. Dry the sand at 105°C. Sift to remove any remaining silt and weigh. Express results as a percentage of total soil mass and multiply by 2.

Demonstrations

The use of the pipette method for determination of particle size distribution will be demonstrated, and students will be given data to plot a summation curve for determining median size (D_{50}) and the Uniformity Coefficient (D_{50}/D_{10}).

Pipette Method

The pipette method is often used as a standard method for the particle size analysis to which other methods are compared. This procedure has been adapted from Day (1965) and Green (1981).

Apparatus and Reagents

1. Beakers – 100 to 1000 mL, centrifuge bottles, both glass and plastic – 250 mL
2. Centrifuges – low speed, about 1500 rpm, and high speed, about 12,000 rpm, with 250 mL bottles.
3. Filter candle – porous ceramic tube, 0.05 MPa (0.5 bar) pressure rated.
4. Shakers – horizontal reciprocating shaker, sieve shaker, wrist action shaker, holders for 250 mL centrifuge bottles on paint shaker.
5. Cylinders – 1000 mL (height of 1000 mL mark, 36 ± 2 cm).

6. Large (no. 13) rubber stoppers for 100 mL cylinder.
7. Stirrers – electric stirrers for mechanical mixing, hand stirrer made by joining a brass rod about 50 cm long to the center of a thin, circular piece of perforated brass or plastic sheeting.
8. Pipette rack – device to permit sliding the pipette laterally and lowering the pipette to a precise depth in the sedimentation cylinder (Clark, 1962; Day, 1965; see also Fig. 15.4).
9. Weighing bottles – (beakers can be used).
10. Set of sieves – square mesh with bronze wire cloth, 7.6 cm (3 in.) diameter with the following openings: 1000, 500, 250, 106, 53 or 47 µm.

Determination

Transfer the dried sand to the nest of sieves arranged from top to bottom with decreasing size in the following order: 1000, 500, 250, 106, 53 µm and pan. Shake the sieves on a sieve shaker. A 3-min shaking time is usually adequate. Weigh each sand fraction and the residual silt and clay that passed through the 53 µm (270 mesh) sieve. Weighing precision of 0.01 g is adequate.

Determination of silt and clay (< 2 µm)

Place the cylinder containing the silt and clay suspension in a water bath; add 10 mL of HMP solution and make up to 1 L volume with distilled water; cover with a watch glass. Let the suspension stand at least several hours to equilibrate.

After equilibration, stir the suspension thoroughly with a hand stirrer for at least 30 s using and up-and-down motion. Note the time at completion of stirring and the temperature of the water bath. It is convenient to complete stirring adjacent suspensions at intervals of about 3 min. An alternative to hand stirring is stoppering the sedimentation cylinder and shaking end-over-end for 1 min.

After the appropriate time interval, lower the closed Lowy pipette carefully to the appropriate depth, turn on the vacuum, and with draw a 25 mL sample in about 12 s. A device for controlling the vacuum is required (Fig. 1).

Discharge the sample into a tared and numbered weighing bottle, beaker, or aluminum dish. Rinse the pipette with distilled water and add the rinse water to the clay suspension in the weighing bottle. Evaporate the water, dry the clay at 105°C, cool in a desiccator, and weigh.

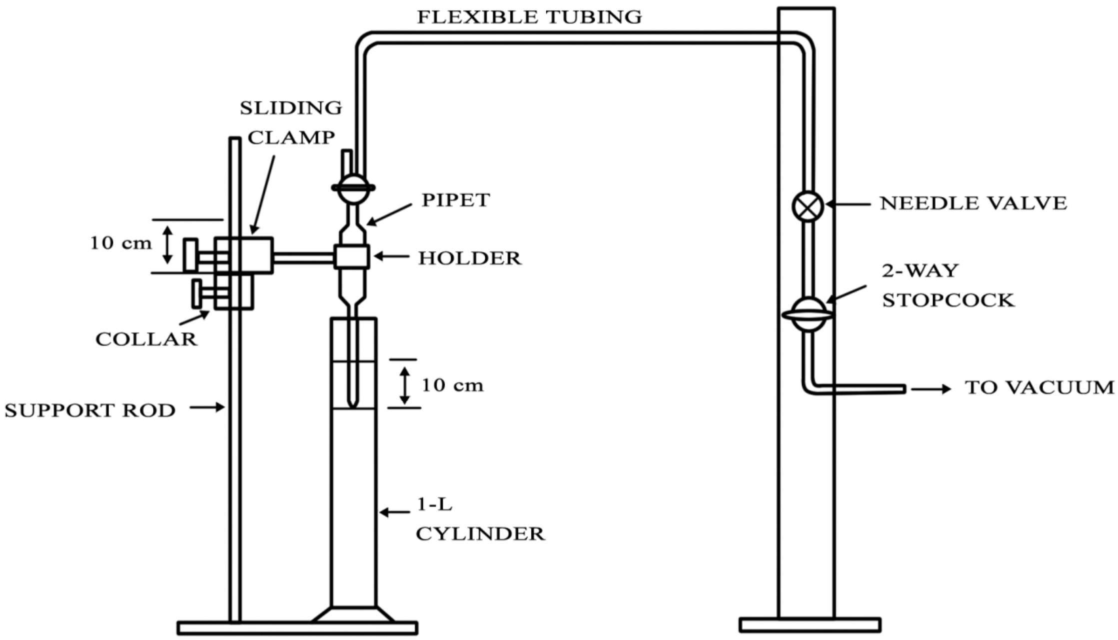

Fig. 1. Schematic of pipet stand and apparatus for sedimentation analysis.

Other Methods

In addition to sieving and sedimentation procedures, there are numerous techniques for measurement of particle-sized distribution that have been developed for powder technology and other applications. These techniques include optical microscopy, transmission electron microscopy (TEM), scanning electron microscopy (SEM), electrical sensory zone (Coulter counter) methods, and light-scattering methods such as laser-light scattering, turbidimeters, holography, and x-ray centrifuges. An excellent discussion of these and other methods for particle-size distribution is given by Allen (1981).

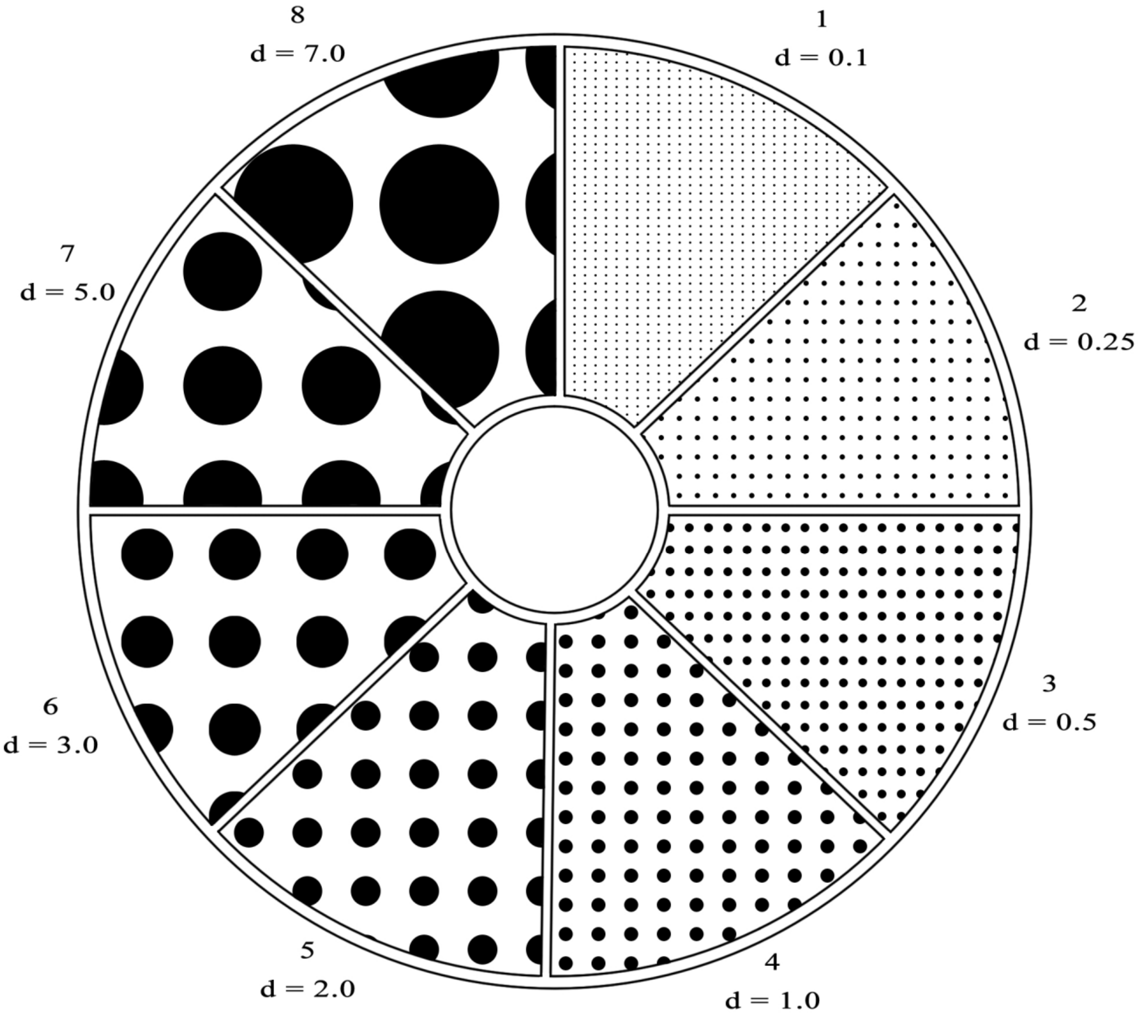

Fig. 2. Sizes of particles of indicated diameters (d) in units of mm.

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Practical 4: Aggregate Stability

Much of the interest in soil structure may be ascribed to the fact that many important soil phenomena such as aeration, movement and retention of water, and root penetration are influenced by the nature of the soil structure. Determination of total aggregation, strength and size distribution of aggregates are the direct measurements of soil structure. In addition, the number, size, distribution, and configuration of the voids within and between aggregates are also intimately associated with soil structure. In fact, most methods of evaluation soil structure involve either direct measurement of some characteristic of the aggregates, indirect measurement of soil pore space or implicit evaluation of such pore spaces from other data. In measuring soil structure by means of aggregate analysis for example, the investigator is concerned directly with the size-distribution of aggregates but indirectly with the size-distribution of the soil voids associated with each particular aggregate size-distribution.

The water-stability of soil aggregates is an important physical characteristic of cultivated soils. It measures the extent to which soil aggregates are likely to remain intact and separate from one another through subsequent rain and mechanical disturbance. Two of the following methods of testing the stability of soil aggregates prepared in the laboratory [A and B] are described in detail below.

[A] Dry-sieving the aggregates and determining their size distribution by sieving over nested sieves. (Chepil, 1962).

[B] Wet-sieving the aggregates, i.e., placing them on a sieve which is agitated under water. The proportion of aggregates remaining on the sieve is taken as a measure of stability (Yoder, 1936).

[C] Williams' method of packing aggregates in a container, flooding them with water, agitating them, and noting the amount of water subsequently extractable from the bed of aggregates by a low tension (Williams, 1963). In this method, the collapse of unstable aggregates leads to a choking of the open spaces among the aggregates with pulverized soil, thus causing a reduction of the water extractable from these spaces at low tensions.

A. Determination of the aggregation by dry sieving

The degree of aggregation may be defined as the ratio of the percent of compound particles of sizes >d formed from primary particles <d to the percent of primary particles of sizes <d.

For convenience d may be taken as the limiting size of particles retained by the 0.2 mm (72 mesh) sieve. The denominator of the above ratio is then known from the mechanical analysis of the soil (fine sand + silt + clay).

Equipment

a) A 0.2 mm opening sieve (number 72 mesh)
b) A balance weighing to 0.01 g capacity.

Procedure for dry-sieving

A relevant procedure for assessment of the wind erosion risks is the "rotary sieving method" (Chepil, 1962). Two other simplified procedures are hand sieving and a nested sieve shaker technique. The hand sieving method is described below:

Weigh accurately about 1 ± 0.2 g of 2-mm air-dry soil and transfer to a weighed sieve. Shake by hand over a sheet of paper until no further material passes through and then reweigh the sieve. The material retained contains coarse sand particles + aggregates composed of fine sand, silt, and clay particles.

If: M = initial mass of air dry soil
B = mass of material retained on the sieve
A = mass of coarse sand particles (from mechanical analysis)
Then, degree of aggregation (%) = $[(B - A) / (M - A)] * 100$

Dry sieving for aggregates

Weigh 20 ± 0.3 g of aggregates 74.75 mm. Use nested sieves 4.75, 2.1, 0.5, 0.25, and shake them on a shaker for about 15 minutes. Remove sieves and weigh contents on each sieve. Use 9-e and k for calculating aggregation.

B. Determination of aggregation by wet sieving

Initial soil aggregate preparation for water-stability tests

Obtain about 300 g of air-dried bulk soil. Crush, by hand or mallet, the larger clods and pass the sample through a nested pair of openings 8 mm (top) and 5 mm (bottom). Again crush the large aggregates retained on the top sieve and pass through the sieve-pair. Collect about 150 g of soil aggregates retained on the 5 mm sieve. Remove roots and other plant material and store the aggregates for analysis.

Apparatus

The wet-sieving device is comprised of 12 sets of nested sieves suspended from a bar which is oscillated by a shaft and crank system driven by an electric motor moving at approximately 1 oscillation per 2 seconds or 30 oscillations per minute. The nested sets of sieves move up-and-down through a vertical distance of about 3 cm submerged in tanks (approx. dimensions: 20 x 20 x 40 cm) of water. The sieves of opening diameters 4.75, 2, 1, 0.5, and 0.2 mm are stacked, in descending sequence, with the 4.75 mm sieve on top. The wet sieving apparatus is located in KH, Room 437.

Procedure for wet-sieving

1. Weigh out about 51 g duplicate sub-samples of previously air-dried aggregates (passed through 8 mm and retained on 5 mm sieves) of the soil provided. It is advisable to equilibrate aggregates at 98% relative humidity in a vacuum desiccator for 1 week prior to wet-sieving. Sulfuric acid is used for this purpose.

2. Weigh an additional approx. 25 g sub-sample of aggregates for water content determination. Record the mass and place in oven 105˚C.
3. Place the duplicate 50 g aggregate sub-samples gently onto the top (4.75 mm) sieve of two nested sieve sets on the wet-sieving apparatus.
4. Making sure the shaft and crank are such that the sieves rest in their lowest position, slowly bring the level of the water in the tanks to where they just begin to wet up the aggregates sitting on the top sieve.
5. Allow the aggregates to gradually pre-wet under tension for 30 minutes.
6. Turn on the mechanical sieving apparatus and set the timer to 30 minutes.
7. Upon completion of wet-sieving, allow the water from each nest of sieves to drain into their respective tanks for about 3 min.
8. Separate the sieves by prying them apart gently with a putty knife.
9. Pour and wash out the contents of each sieve into a container and let settle for 24 h. Then carefully decant off excess water making sure not to lose soil.
10. Transfer contents to labeled beakers, keeping track of sieve sizes and color of beaker labels, and dry beakers in oven at 105˚C.
11. After drying for 24 hours, weigh and record the contents of each beaker.
12. Make sure to account for gravel content in gravelly samples. To do this, wash the soil sample from each sieve (following wet-sieving) through a sieve with 2 mm openings. Collect both the primary particles that passed through the sieve and the gravel remaining on the sieves into separate beakers, and dry them in the oven. Subtract the gravel content from the total soil sample before computing the aggregate stability parameters.

Calculations

1. Percent Water Stable Aggregates

M_0 = total mass of aggregates, 8 to 4.75 mm in diameter

M_1 = mass of aggregates retained on 4.75 mm sieve

M_2 = mass of aggregates retained on 2 mm sieve

M_3 = mass of aggregates retained on 1 mm sieve

M_4 = mass of aggregates retained on 0.5 mm sieve

M_5 = mass of aggregates retained on 0.25 mm sieve

M_6 = mass of sand fraction retained on 4.75 mm sieve

M_7 = mass of sand fraction retained on 2 mm sieve

a) %WSA between 8.0 and 4.75 mm = 100 * M_1/M_0
b) %WSA between 4.75 and 2.0 mm = 100 * M_2/M_0
c) %WSA between 2.0 and 1.0 mm = 100 * M_3/M_0
d) %WSA between 1.0 and 0.5 mm = 100 * M_4/M_0
e) %WSA between 0.5 and 0.25 mm = 100 * M_5/M_0
f) %WSA between 8.0 and 4.75 mm, after correction for primary particles = 100 * $(M_1 - M_6) / M_0$
g) %WSA between 4.75 and 2.0 mm, after correction for primary particles = 100 * $(M_2 - M_7) / M_0$
h) % total aggregation = % WSA > 0.25 = 100 * $(M_1 + M_2 + M_3 + M_4 + M_5) / M_0$
i) % total aggregation, after correction for primary particles = 100 * $(M_1 + M_2 + M_3 + M_4 + M_5 – M_5 – M_6 + M_7 – M_8 – M_9 – M_{10}) / M_0$ (students of SS671 do not need to do this.)

2. Geometric mean diameter

$$GMD = \frac{\exp\left(\sum_{i=1}^{n} m_i \log x_i\right)}{\sum_{i=1}^{n} m_i} \qquad \text{(Equation 1)}$$

where,

n = the number of aggregate size ranges (mm), and

m_i = the mass of aggregates in a size class of average diameter x_i.

3. Mean weight diameter

$$MWD = \sum_{j=1}^{n} x_j m_j \qquad \text{(Equation 2)}$$

where,

n = the number of aggregate size ranges (mm),

mj = mass of the aggregates of that size range as a fraction of the total dry mass of the sample analyzed, and

xj = mean diameter of any particular size range of aggregates separated by sieving.

Eqation 2 has been shown to over-estimate the MWD (youker and McGuinness, 1956; Kemper and Roenau, 1986). Therefore, equation 3 is used to adjust these values.

$MWD_c = 0.876(MWD) - 0.079$ (Equation 3)

Where, MWD_c is the corrected MWD. Equation 3 may have to be developed for soil specific conditions.

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Practical 5: Tensile strength of aggregates

INTRODUCTION

Aggregate strength is an important soil mechanical attribute that affects the soil structural behavior. It controls root penetration, plant growth, seedbed preparation, compaction, soil erosion, and other soil physical, mechanical, and hydrological properties and processes. Root development and crop production decrease significantly with increasing soil aggregate strength (Horn and Dexter, 1989). Aggregate strength is often quantified by measuring its tensile strength (TS), which is one of the most sensitive mechanical properties of aggregates. The TS refers to the stress or force required to rupture an individual aggregate. The TS is a dynamic indicator of the structural condition of the whole soil (Fi.g 1).

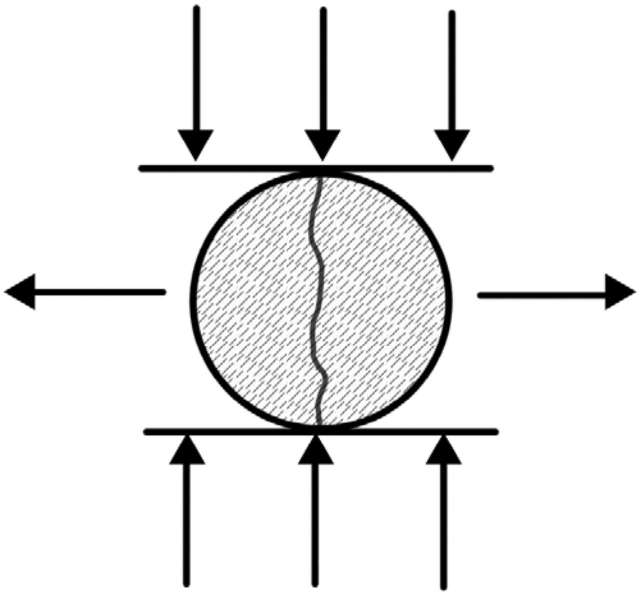

Fig. 1. Rupture of a soil aggregate under applied force.

The TS measures the strength of inter-particle bonds of the soil aggregates and is used as an indicator of the magnitude of soil aggregation. The TS is a function of the interactive effects of water content, clay content and mineralogy, cementing compounds, and organic matter content of soil aggregates. The relationships of TS with other soil properties depend on tillage-crop management practices and site-specific conditions. The hierarchal organization or architecture of soil aggregates is dictated by the TS. Microaggregates often have higher TS values than macroaggregates because large aggregates because large aggregates have more planes of failure, more macropores and micro-cracks, and coarser organic residues. Despite its importance, TS is not commonly measured and reported in soil surveys. Yet, gaining an understanding of TS properties of individual soil aggregates is vital to soil management and cropping systems.

Determination of Tensile Strength

The TS of aggregates can be determined using direct or indirect tension (crushing test) methods. The direct tension test determines the fracture of soil aggregates perpendicular to the forces applied. A major challenge to use the direct test is the difficulty of preparing samples. In addition, the direct test is more suitable for large aggregates or clods, which are either remolded or grooved in two cups for the TS measurement. Thus, indirect tension test is commonly used to measure the TS. Simple and sophisticated devices are available for the indirect tests. The indirect test consists of placing an aggregate between two parallel plates and then applying an amount of force to an aggregate at a constant rate of displacement until it fractures. The TS (kPa) is then computed by using Eq. [1] (Rogowski, et al., 1968).

$$TS0.576 = F\left(\frac{\square}{d_{agg}\left(\square^{2}\right)}\right) \qquad [1]$$

Where F is the vertical breaking force (N) applied to rupture the aggregate, d_{agg} is the mean aggregate diameter (m), and k is a coefficient (~0.576).

Simple crushing apparatus

In this laboratory practical, a simple apparatus based on a design by Horn and Dexter (1989) will be used to determine the TS of aggregates. The apparatus consists of two parallel arms connected through a hinge and equipped with parallel round plates to hold the soil aggregate. The upper arm is made of aluminum channel for lightness and mobility compared to the lower arm, which is attached to a laboratory table for stability. Each arm has locating holes to adjust the plates according to the strength of the aggregate. The upper arm has a counter-mass at the rear end to balance and to prevent the arm from exerting a net force on the aggregate. A hook at the front end of the upper arm is fitted to hold a plastic bucket (Fig. 2).

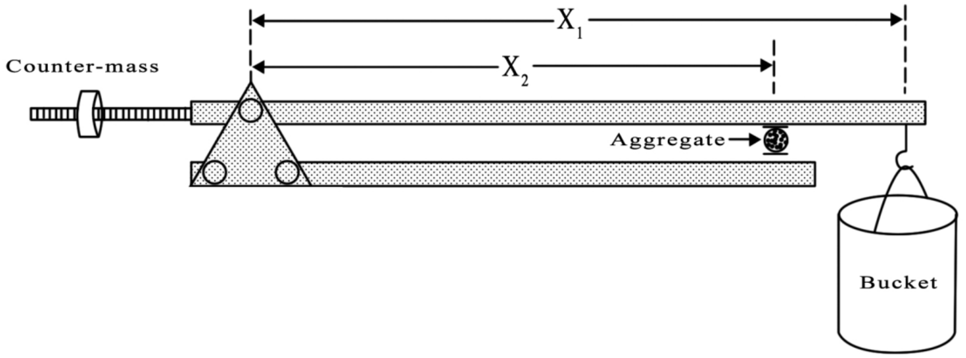

Fig. 2. Crushing test apparatus for the determination of the tensile strength of aggregates.

Procedures for the crushing test

1. Obtain the following three fractions of aggregate sizes: 2-4, 4-6, 6-8 mm by sieving previously oven-dried and crushed bulk soil samples.
2. Store each aggregate fraction in labeled bags.
3. Set up the crushing test device and hang a previously weighed empty bucket through the hook as shown in Fig 2.
4. Place an individual aggregate between the two round plates of the crushing apparatus at a given distance from the hinge where appropriate.
5. Determine the TS on five aggregates (replicates) for each size fraction to account for the high variability of the TS values.
6. Run water slowly into the bucket at about 1 L min^{-1} through a single-control faucet until the aggregate crushes.
7. Maintain your control over the faucet while observing the aggregate so as to determine the exact moment of breakage.
8. Stop the inflow of water at aggregate failure.

9. The failure of an aggregate can be estimated by a sudden collapse or appearance of a visible crack across the aggregate. Detection of failure may be somewhat difficult requiring the testing of a number of replications.
10. Weigh the bucket plus water and record the total mass.
11. Estimate the d_{agg} of each soil aggregate using the approaches outlined by Dexter and Kroesbergen (1985).

Approach 1: compute the average of the diameter of upper (s_1) and lower (s_2) sieve sizes to compute the d_{agg} for the 1-2 and 2-4 mm using Eq. 2

$$Method\ 1: d_{agg} = \frac{s_1 + s_2}{2} \qquad [2]$$

Approach 2: measure the diameter of the individual aggregates with a caliper for the 8-6 and 6-4 mm aggregates in addition to using "Method 1."

12. Record the longest, intermediate, smallest diameter of each aggregate to estimate the final diameter using Eq [3].

$$Method\ 2: d_{agg} = \frac{dx + dy + dz}{3} \qquad [3]$$

13. Calculate the breaking force (F) at failure as Eq. [4].

$$F = Ma\left(\frac{x_1}{x_2}\right) \qquad [4]$$

where M is the mass of the water in the bucket (g), a is the acceleration due to gravity (9.81 m s^{-2}), x_1 is the distance of the hook from the hinge or pivot (m), and x_2 is the distance of the plate from the hinge (m).

14. Finally, compute the TS of aggregates using Eq. [1].

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Practical 6: Soil Water Characteristics

Soil water retention is a function of particle and pore size distributions and, as such, is an indictor of plant available water capacity, aeration, and soil quality. Sandy soils have less water holding capacity than clayey soils because coarse-textured soils possess more macropores. Structure, stability, and organic matter content of the soil significantly affect water retention through their influence on pore size distribution. Clays absorb water into their crystalline structure and thus retain water more tightly than sandy soils through capillary forces. Any characterization of soils, such as the soil survey, typically includes values of water content at 0.03 MPa (Field Capacity, FC) and 1.5 MPa (Permanent Wilting Point, PWP), and their difference, the Available Water Capacity (AWC). This laboratory practical involves the determination of these critical values, and the air-filled porosity at 0.006 MPa, a factor important in drainage and soil aeration.

A. High energy soil water characteristics

High energy soil water characteristics involve measurements of the soil water content/soil water potential relationship for low suction within the range of saturation point (0 MPa) and 0.01 MPa suction. These measurements can be done by using:

(i) sintered or fritted glass plates,
(ii) porous plastic membrane,
(iii) Sand Box method, or
(iv) Tension Table.

Procedure

Duplicate soil cores are provided to each student for this practical. These cores should be handled with care to ensure that the natural field state of the soil is simulated in the form of intact soil cores.

Place two layers of cheese-cloth over the bottom end of the core and secure it with a rubber band. Saturate the soil by placing the cores in a pan containing about 1 cm of water and allowing capillary action to wet the core up to the surface. Slowly add water to the pan until the water level is about 2 cm from the top of the core and let samples set overnight. The metal cylinder mass is M_1 (from previous practical). Weigh the saturated cores, after wiping outer surface dry with a paper towel, and designate the combined mass of soil and metal cylinder as M_2.

Study the operation of the Tension Table in the laboratory and adjust the water level in the overflow bottle until a tension of 60 cm (0.006 MPa) of water is obtained on the blotter paper. Place the cores on the Tension Table and cover the tray to prevent evaporation. Let cores remain on the tension table for about 24 hours with periodic checking to make sure that the water column has not been broken by air entry. Remove the soil cores and weigh. Designate this mass as M_3.

B. Low energy soil water characteristics

Low energy soil water characteristics involve measurements of the soil water content/soil water potential relationship for high suction within the range of 0.01 MPa and 1.5 MPa suction (PWP). These measurements can be done by using:

(i) pressure plate extractors,
(ii) filter paper techniques, or
(iii) relative humidity chambers.

Ceramic Plate Extractors

Ceramic plate extractors can be used for extracting water from soil over a suction (negative pressure) range of 0.01 to 1.5 MPa. There are three major considerations in designing extractors:

1. The suction range over which the ceramic plates are operative, as determined by the pore size.
2. The time required for water equilibrium established in the soil samples, and
3. The safety features involved in the use of extractors.

The ceramic plates are operative as long as water films occupy the pores. The suction range over which this occurs is dependent on the size of the largest pore radii in the plate. The water film in the pores does not break until the pressure in the chamber exceeds $2\sigma/r$ where σ is the surface tension of water and r is the radius of curvature of the water film. The radius of curvature is approximately equal to the radius of the pore opening. Thus, a ceramic plate having only small openings operates over a much larger range of external gas pressures than a plate having larger pores. Therefore, the water content-water potential relationship can be used to estimate the pore size distribution of a soil.

The time for reaching equilibrium between the water suction in the plate and in the soil is largely dependent on the rate at which water can be transmitted through the plate. (NOTE: the thickness of the soil sample is important, since the time to reach equilibrium varies as the square of the sample heights). The rate of water transmission is proportional to r^2, where r is again the pore radius of the plate. Thus to reduce extraction time, a ceramic plate with relatively large pore radii is used for extracting water below 0.2 MPa suction. (NOTE: for the same reason, blotter paper replaces a ceramic plate for extracting water at suctions less than 0.01 MPa). The need for safety features and thick walls in an extractor having 1.5 MPa suction is self evident.

Principles of Operation

As soon as gas pressure inside the vessel is raised above atmospheric pressure, the higher pressure inside the vessel forces excess water through the microscopic pores in the ceramic plates. The high pressure gas, however, does not flow through the pores as they are filled with water and the surface tension of the water at the gas-liquid interface at each of the pores supports the pressure much the same as a flexible rubber diaphragm. When the gas pressure is increased inside the extractor the radius of curvature of this surface decreases. However, the water film will not break and let gas pass throughout the whole pressure range of the extractor, from 0 to 1.5 MPa.

At any given gas pressure in the chamber, soil water will flow from around each soil particle and out through the ceramic plate until such time as the effective curvature of the water film throughout the soil is the same as that of the pores in the ceramic plate. At this point, equilibrium is reached where the flow of water in the system ceases. As the gas pressure in the extractor is increased, flow of soil water from the samples starts again and continues until a new equilibrium is established. At equilibrium, there is an exact relationship between the gas pressure in the extractor and the soil suction (and hence the water content) in the samples. For example, if the gas pressure in the extractor is maintained at 0.1 MPa (15 PSI), the soil suction in the samples at equilibrium will be at 0.1 MPa. If the gas pressure is maintained at 1.5 MPa, (225 PSI), the soil samples will equilibrate at 1.5 MPa suction, the approximate wilting point for all soils.

a. Procedure for 0.03 MPa extractor

Study the operation of the porous pressure-plate apparatus which is used to extract soil water with pressures ranging from 0.01 to 0.4 MPa. Remove the cheesecloth from the soil cores and press the soil evenly over its upper end until the soil extends about 5 mm from its lower end. Place the protruding end of the soil against the porous ceramic plates, secure the top of the extractor, and apply 5 psi (0.03 MPa) air pressure to the soil. Let the soil remain at 0.03 MPa pressure until water no longer drips from the outlet. When this occurs, release the pressure, remove and weigh the soil core, and record the mass as M_4.

b. Procedure for 1.5 MPa extractor

The 1.5 MPa Ceramic plate extractor can be used for studies involving the water relationships in soils at high suction. All types of soil samples may be used with the exception of fine clay soil that experience considerable shrinkage as water is removed. This type of soil will shrink away from the ceramic plate in the 15-bar extraction and the reduced flow area will not permit the sample to reach equilibrium. Study the operation of the 1.5 MPa extractor. Prepare duplicate 25 g samples that have been passed through a 2 mm sieve, for each soil type to be run. Place soil sample retaining rings on the ceramic plate to receive the soil samples. Each ceramic plate will accommodate 12 samples when retained in these rings. In order to avoid particle-size segregation, pour all the soil sample from each container into one ring. Pouring out part of the sample and leaving part in one container will give a non-representative sample. Pat down and level the samples in the ring with a spatula, cover with squares of waxed paper, and allow the samples to stand for at least 16 hours with an excess of water on the plate, but without submerging the soil.

Loading the Extractor: When the samples are ready for the extractor, remove the excess water from the ceramic plates with a pipette or syringe, mount the plates in the extractor and connect with the outflow tubes. Be sure the triangular support is in the bottom of the vessel. Use the plastic spacers to separate the plates. Close all unused outlets with the plug bolts that are provided. Be sure the "0" ring is in place, mount the lid, and screw down the clamping bolts, using finger pressure only.

As the pressure builds up inside the extractor, there will be a rush of air from the outflow tubes. This is caused by the reduction of the internal volume of the pressure plate as the diaphragm and screen collapse under the pressure in the extractor.

Removal of Samples: Samples may be removed when water outflow from the tubes ceases and equilibrium is attained. Most soils will approach hydraulic equilibrium within 18 or 20 hours.

At the close of a run, the external outflow tubes should be pinched off to prevent possible back flow of water when the pressure in the extractor is released. Immediately after the pressure regulator is shut off and the pressure exhausted from the extractor, remove the clamping bolts and the lid. Transfer samples to boxes as soon as possible after the release of pressure in order to avoid changes in the water content. Oven-dry to determine water content at 15 bar (M_{pwp}).

Results

1. Calculate for each soil core: a) total porosity, f; b) air porosity at 0.006 MPa suction, f_a; c) water content at 0.03 MPa suction θ_{fc}; and d) water content at 1.5 MPa suction θ_{pwp}.
2. Sketch and label the component parts of: a) the tension table used to extract water at suctions from 0 to 0.006 MPa of water, and b) the porous plate apparatus for extracting water at 0.01-0.4 MPa suctions.
3. Using a particle density of 2.70 g cm^{-3}, calculate f from the equation: $f = [1 - (\rho_b / \rho_s)]$. Tabulate calculated and experimental f values.

Calculations

1. Gravimetric water content at 0.03 MPa,

$M_{fc} = (M_4 - M_5 - M_1) / (M_5 - M_1)$, where M_5 is the dry soil mass from Practical 1.

2. Total porosity, $f = (M_2 - M_1 - M_5) / (V_t * \rho_w)$

3. Volumetric water content at 0.006 MPa suction:

$\theta_{60} = (M_3 - M_1 - M_5) / (V_t * \rho_w)$

4. Porosity at 0.006 MPa suction, $f_a = f - \theta_{60}$

5. Volumetric water content at 0.04 MPa suction,

$\theta_{fc} = M_{fc} * (\rho_b / \rho_w)$,

where ρ_b is the bulk density from Practical 1.

6. Volumetric water content at 1.5 MPa, $\theta_{pwp} = M_{pwp} * \rho_b / \rho_w$.

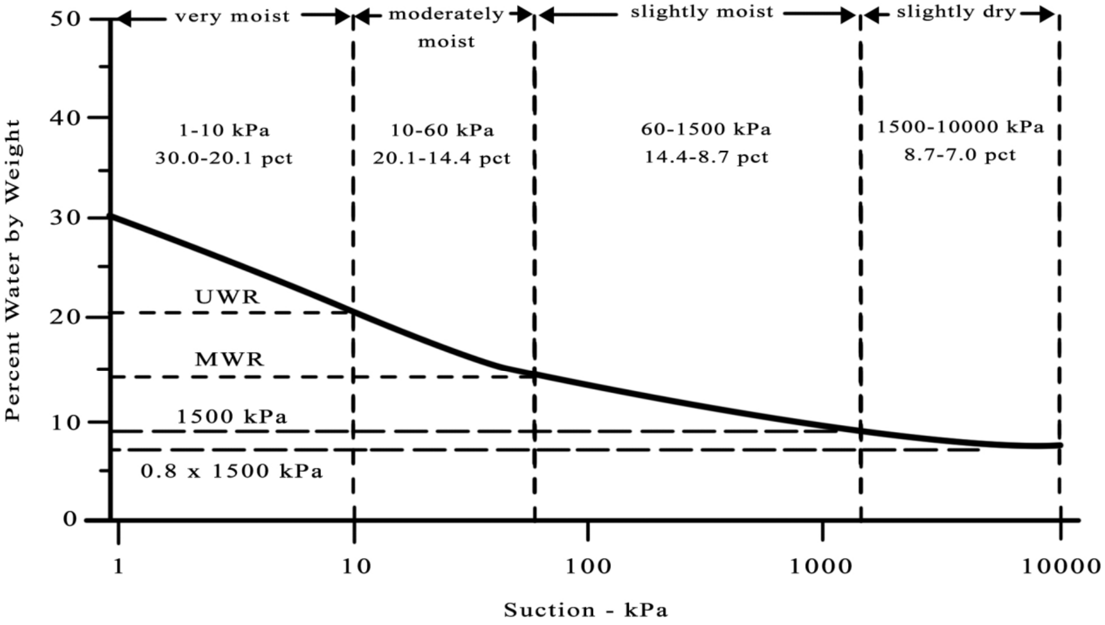

Figure 4.1. Model-based curve for a medium-textured horizon and the relationships of water state class limits to water contents determined from the desorption curve (Soil Survey Staff, 1993).

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Practical 7: Saturated Hydraulic Conductivity

Quantitative assessment of the rate of water movement under saturated conditions through soil is needed to assess drainage status, soil-water balance, potential overland flow, deep percolation, and environmental impact of hydrological events. An important physical/hydrological property that determines the rate of water transmission through the soil is the saturated hydraulic conductivity (K_s). It is a measure of the ability of soil to transmit water.

Darcy's law relates the velocity of flow of a liquid through a porous medium with the driving force, that is, the force causing the flow through the medium (Eq 1):

$$q = -K\nabla H \qquad [1]$$

where q is the velocity flux or the specific discharge rate (cm/hr), K is the hydraulic conductivity (cm/hr), H, the hydraulic head, is the driving force (cm), and ∇ H is the gradient of the hydraulic head in three dimensional space. The flow in one dimension is represented as follows (Eq. 2):

$$q = -K\frac{dH}{dx} \qquad [2]$$

There are two broad categories of methods used to measure saturated hydraulic conductivity: (i) field methods, and (ii) laboratory techniques. Data on field methods (Klute and Dirkson, 1986) are suited for assessment of drainage conditions. Laboratory techniques are relatively simple but the data require careful analyses for use under field conditions.

There are two methods of measuring saturated hydraulic conductivity in the laboratory: (i) constant head permeameter method, and (ii) falling head permeameter method. A schematic of a constant head permeameter to be used in the laboratory is shown in Figure 5.1.

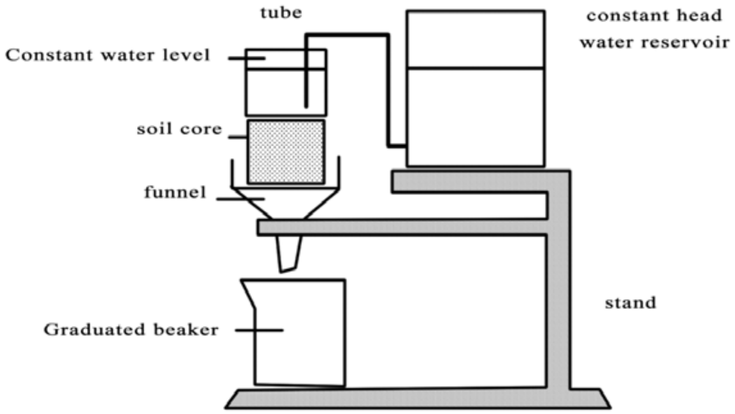

Figure 5.1 Schematic of the constant head permeameter.

Constant Head Permeameter

Procedure

1. Use the undisturbed field soil core previously used for bulk density and water retention.
2. Place a second empty core flush on the top of the soil core and seal with duct tape so that the joint is water tight. Put a circular filter paper on the surface of the soil core.
3. Soak the core over night by placing in tub and gradually filling the tub with water submerging the sample to about ¾ of its height.
4. Turn on and adjust the water inflow to the reservoir such that a desired level is maintained.

5. The rate of inflow and outflow should be adjusted to ensure a constant head (H) above the soil sample. The water temperature should also be maintained constant.
6. Place the soaked core on a meshed Buchner funnel held in a stand and slowly pour water into the upper cylinder using a siphon from the water reservoir such that the empty upper core is $^{2}/_{3}$ to ¾ full. Care must be taken to avoid water overflowing from the top of the upper core.
7. After the water in the top core stabilizes (about 30 minutes), empty the collection beaker or cylinder under the funnel, note and record the initial time, and replace the beaker.
8. Measure the volume of water (Q) that passes through the soil core into the collection beaker in a known time, t = 30 minutes.
9. Measure the height of water above the soil core and record the temperature of the water.

Repeat flow measurements, steps 8 through 9 least three times.

Calculations

a) Saturated hydraulic conductivity is calculated using the following formula:

$$K_S = \frac{Q}{A\,t} * \frac{L}{H}$$

where: K_s = proportionality factor (cm/hr)

Q = volume (cm^3)

A = cross-sectional area of soil core (cm^2)

t = time interval (30 minutes)

L = length of sample (cm)

H = hydraulic head (cm)

b) Intrinsic permeability, $k = \frac{K_s n}{\rho_w g}$

where: n = viscosity of water (centipoises)

ρ_w = density of water (Mg/m^3)

g = acceleration due to gravity, ($9.6\ m/s^2$)

[Look up the values and units of n and ρ_w at the corresponding water temperature in the Handbook of Chemistry and Physics.]

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Practical 8: Watershed management and hydrology

The North Appalachian Experimental Watershed research station is under the jurisdiction of the Agricultural Research Service of the USDA and is operated in cooperation with the Ohio Agricultural Research and Development Center (OARDC) and The Ohio State University. The focus of the research is the study of the effects of crop rotation, tillage tools, and pasture grazing schemes on the movement of sediment, plant nutrients, and pesticides in surface and subsurface waters. Flood hydrology and the effects of surface mining small watersheds are also studied using watersheds and lysimeters. Meteorological stations measure evaporation, precipitation, solar radiation, air temperature, humidity, wind movement, and soil temperature.

Field Trip/Demonstration

At Coshocton, you will observe the weighing monolith lysimeter, the Coshocton Wheel, flumes, weirs, and various land use and management systems.

Website:

http://www.ars-grin.gov/ars//Midwest/Coshocton

Practical 9: Infiltration

Water infiltration generally implies rate of water entry into the soil. The cumulative infiltration (I) refers to the total amount of water infiltrated. Slope of the curve relating cumulative infiltration with time (t) refers to the instantaneous infiltration rate (i) at the time. The equilibrium infiltration rate (i_c) is the slope of I vs. t at long time, usually 3 hours or more.

Theory

On the basis of the water profile following infiltration under ponded conditions, a wetted column can be divided in four identifiable zones: 1) saturated zone 1-3 cm deep from the surface; 2) transmission zone, between the saturated zone (above) and the wetting zone (beneath), is a region of constant soil water content which elongates with time; 3) wetting zone – a region of rapidly changing water content; and 4) wetting front – the visible limit of water penetration, a region of steep water gradient.

Water flow in laboratory columns follows the laws of unsaturated flow:

a) Horizontal column:

$$\frac{\partial \Theta}{\partial t} - \frac{\partial}{\partial x\left[D(\Theta)\frac{\partial \Theta}{\partial k}\right]}$$

where:

$D(\Theta)$ is soil water diffusivity.

There are two methods to analyze the data on infiltration:

(i) Philip's model: $I = St^{½}$

Where,

I = cumulative infiltration (cm)

S = soil water sorptivity (cm $sec^{½}$)

t = time

(ii) Kostiakov's model: $I = \alpha t^{\beta}$

Where α and β are constants.

b) Vertical column:

$$\frac{\partial \Theta}{\partial t} = \nabla[D(\Theta)\nabla\Theta]$$

Again, there is more than one approach to analyzing the laboratory data:

(i) Philip's model: $I = St^{½} + At$

Where A is soil water transmissivity (cm $\sec^{-1}$)

(ii) Kostiakov's solution: $I = \alpha t^{\beta}$

(iii) Green-Ampt model: $I = b/I + i_c$

Where i = infiltration rate, i_c is steady-state infiltration rate and b = constant.

Objectives

(i) To determine S, A, α, β, and b parameters for soil,

(ii) To test the observation that the cumulative infiltration and wetting front are proportional to $t^{1/2}$ and

(iii) To identify different zones of wetting within the soil columns.

Procedure

1. Weigh the two columns before packing columns with soil to known bulk densities: tap the sides of the columns with a spatula while filling and then weigh the columns and soil.
2. Apply water in horizontal and vertical columns at a constant head using the Marriotte Bottle technique.
3. Record the observations on cumulative infiltration, the advance of the wetting front, and change in the height of surface layer at different times after the onset of the experiment.
4. When the wetting front has penetrated into at least 50% of the column, disconnect the water supply and siphon the excess water from the soil surface. Continue recording observation for at least three hours.

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Practical 10: Atterberg Limits

The liquid and plastic limits of soil are important characteristics of particular interest to agricultural and engineering applications. They affect workability and trafficability of soils as well as ability to support structures. Atterberg limits, named after a Swedish farmer, define the range of water contents at which the soil can be worked for seedbed preparation without deleterious effect on soil structure (Wu, 1981). For details students are referred to reports by Campbell (1991) and Marshall et al (1996). The objective of this lab experiment is to determine the liquid and plastic limits of the soil provided and the related Atterberg constants.

A. Liquid Limits

The liquid limit or upper plastic limit of a soil is defined as the minimum water content at which a mixture of soil and water acts as a viscous fluid. At this condition the water films become so thick the cohesion is reduced and the soil mass flows under an applied force. It is the water content at which most of the films coalesce to fill up the majority of the soil pore spaces.

Apparatus [Casagrande Liquid Limit Device]

The apparatus consists of a brass cup, which is dropped onto a hard rubber base by a cam operated by a crank (Casagrande, 1958). The cup weighs about 200 g. It is hinged at the back to a cam. The cam, mounted on a shaft, is rotated to lift and drop the cup through a fixed distance of about 1 cm (Fig. 11.2).

The grooving tool cuts a trapezoidal groove, 2 mm wide at the bottom, 11 mm wide at the top and 8 mm high. Shoulders on the grooving tool enable the formation of a groove of constant depth and width (Fig. 11.3).

Procedure

1. Obtain 150 g of ground and sieved (through 2 mm) soil.
2. Mix with water to putty-like consistency in an evaporating dish.
3. Place a portion of the wet soil in the brass cup of the device.
4. With a spatula, level off the wet soil in the cup to a depth of 1 cm.
5. With the grooving tool, divide the sample through center line of cam.
6. Turn the crank at a rate of 2 r.p.s. and count the number of revolutions[1] required to bring the two sides of the sample into contact at the bottom of the groove for a distance of 1

---

[1] The objective is to obtain sample of such a consistency that the number of blows range from a minimum of 10 to a maximum of 100. For example, if your first trial required 100 or more revolutions, then add water for your second trail.

cm. The groove should be closed by a flow of the soil and not by slippage between the soil and the cup.

7. If the number of revolutions is in the range 10 to 40, remove a portion of the soil from both sides of the groove for water content determination.
8. Transfer the paste from the device to the evaporating dish and repeat steps 3 – 7 to obtain an average of 3 values of revolutions at each water level.
9. With the paste in the evaporating dish, add more water, mix thoroughly and repeat steps 2 – 8 until at least 4 different sets of values are obtained.

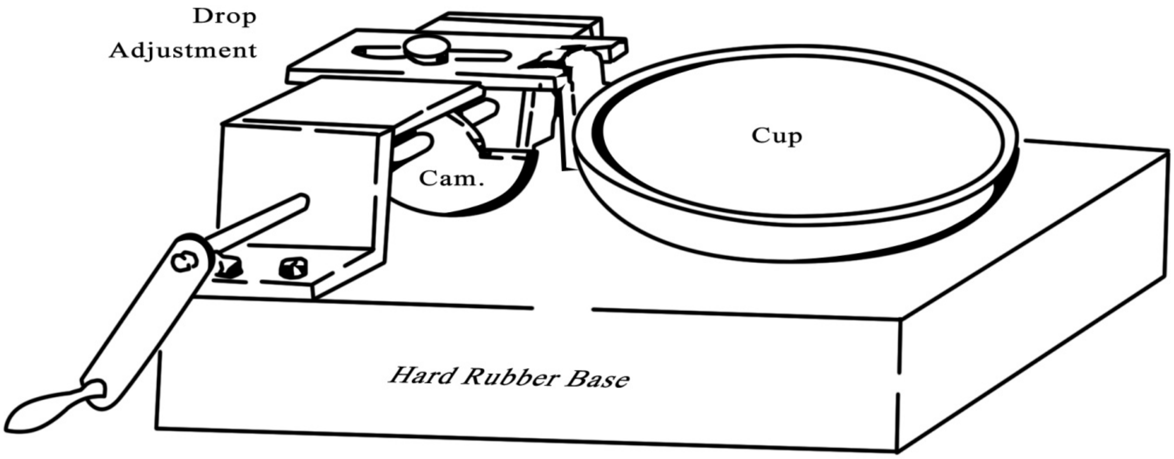


Figure 11.2 Casagrande liquid limit device.

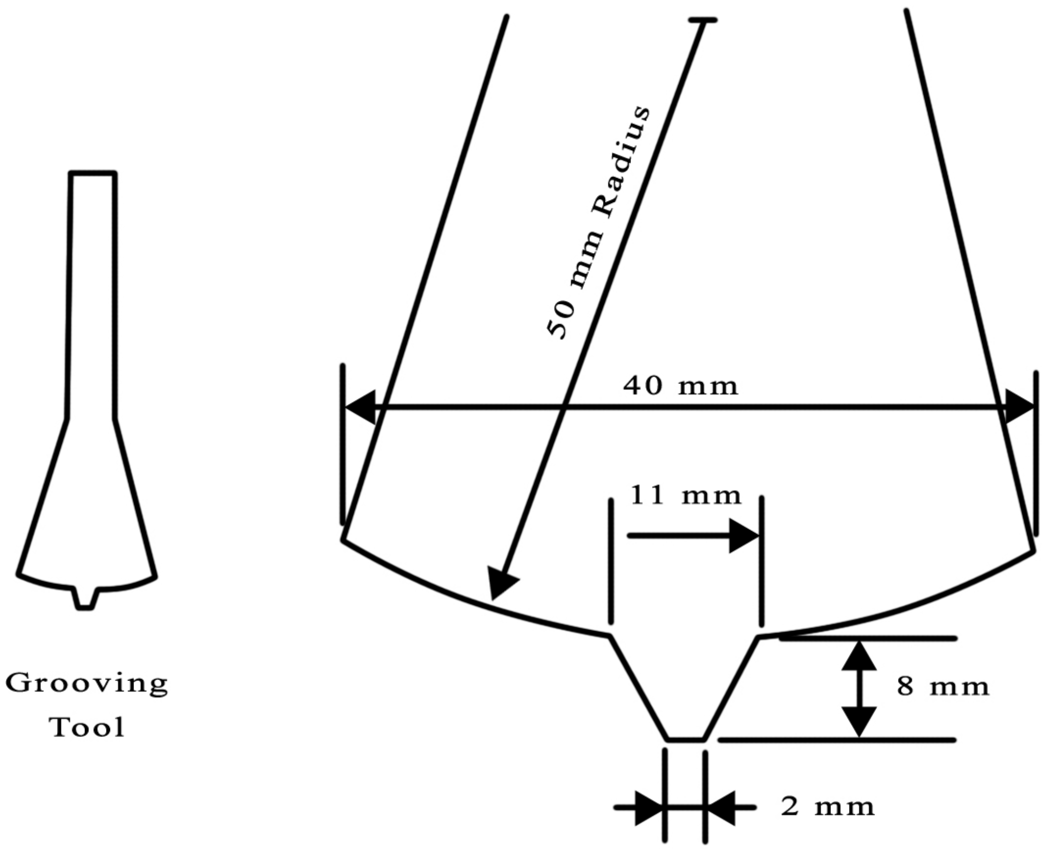


Figure 11.3 Cutting edge of grooving tool.

B. <u>Plastic Limit</u>

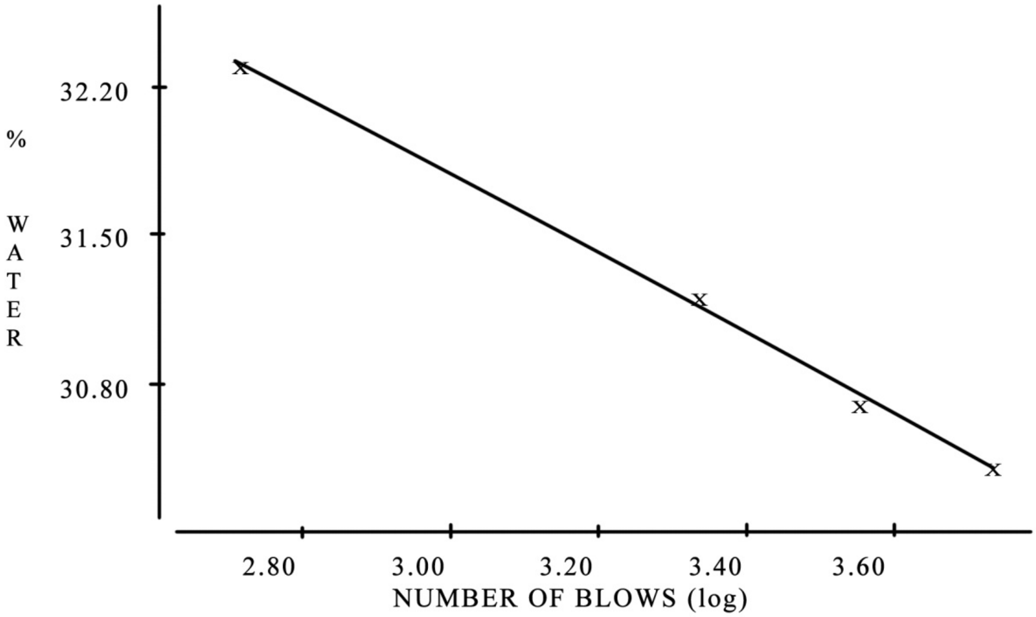
The lower plastic limit represents the water content of the change from the friable to the plastic consistency. Orientation of the particles and their subsequent sliding over each other take place at this point as sufficient water has been added to provide a film around each particle. Experimental evidence shows that cohesion is maximum at the lower plastic limit. The water content at this limit depends on the amount and kind of colloidal material present. The colloid content determines the number of films and the nature of the colloid determines the quantity of water absorbed before a distinct water film is formed around each point of contact.

Procedure

1. Obtain about 25 g of soil sieved through a 0.5 mm sieve.
2. Add water in small quantities and mix until soil begins to lose its crumbly feel and shows a tendency to roll in filaments between the thumb and finger.
3. Form in a ball, place on glass plate (or bench top), and roll with palm of hand.
4. Plastic limit is reached when 1/8 – inch diameter rods of soil 1/4 to 3/8 inch in length can be rolled before crumbling occurs.
5. If soil can be rolled smaller than 1/8 inch, the soil is too wet. Add some more of the sieved soil to the wet soil and mix. Repeat steps 3 and 4.
6. If the soil crumbles before it reaches 1/8 inch diameter, it is too dry. Add a few more drops of water, mix and repeat steps 3 and 4.
7. When the proper water content has been reached (i.e., step 4 is satisfied), take a sample, weigh and place in oven for water content determination.

Atterberg Constants

1. FLOW CURVE represents the relationships between water contents (Y-axis, arithmetic scale) and the corresponding number of revolutions or blows (X-axis, log scale). It is the best-fit straight-line drawn to the data of this lab experiment (Fig. 11.4).
2. LIQUID LIMIT is the water content corresponding to the intersection of the flow curve with the 25 blow ordinate; it may be determined from the equation by solving for Y when X = 25.
3. PLASTIC LIMIT is the water content at which the soil crumbled into 1/8 inch rods upon being rolled out – average values from results of repetitive trials.
4. PLASTICITY INDEX (or PLASTIC NUMBER) is the difference in water contents between liquid limit and plastic limit.
5. FLOW INDEX is the slope of the flow curve or the water content covered by one cycle on the log scale.



Liquid limit = 31.4%
Slope = -4.0

Figure 11.4. Flow curve depicting relationship between water content and number of revolutions or blows.

6.

# Blows:	42	35	28	15
Water content:	30.4	30.7	31.2	32.3

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Practical 11: Air Permeability

Introduction

Air permeability of soils has been recognized as an important parameter for soil aeration and contaminant reduction remediation techniques and is fundamental to our understanding of environmental problems in vadose zone (Kirkham, 1946). In agricultural research knowledge of air-filled pores, pore size distribution, tortuosity, air permeability, and their variation along the cross-section or depth is important to describe aeration, structure, and compaction of the soil. However, precise impact of these parameters on crop yield is soil and crop specific and not known. In general poor structure, low air filled porosity, and low water permeability adversely affect crop yield (Moore and Attenborough, 1992).

Air permeability of porous media including soils is governed by the convective transport of air through the media under a pressure gradient. The gaseous flow, as a consequence of the pressure head difference, is often reported as the mass flow of gas. The other mechanism of gas transport is the diffusion, which occurs due to the change in concentration gradients or the partial pressures of the components of gaseous mix. Under normal circumstances both these processes can occur simultaneously provided the concentration and the pressure gradients exist concurrently. The mass flow of gas is important when differences in pressure are due to the change in barometric pressure, temperature or soil water content. However, diffusion is considered the primary mechanism of gaseous exchange.

In general, soil matrix consists of a mixture of fluid and gaseous phases. Since viscosity of air is small compared to that of water, soil air remains at most phases in the soil matrix at or near atmospheric pressure. A small pressure gradient is sufficient for soil air to move into or out of the soil system. As a result, it has a negligible effect on flow of water. Therefore, most water transport analysis ignores the simultaneous movement of soil air. The negligible influence due to the low-pressure gradients in soil air is generally but not necessarily always true.

Basic Principles

According to Darcy’s law for laminar flow, velocity of a fluid is proportional to the pressure difference and inversely proportional to the pressure difference and inversely proportional to the length of the flow path. Therefore, Darcy’s law is applicable to the airflow through soils. The soil pores and macropores or cracks have the greatest contribution to airflow in the soil. According to the Poiseuille equation, air flow through a single pore varies as the fourth order of the pore radius ($Q \alpha r^4$). Air permeability (k_a, cm^2) can be defined by the following relationship according to Darcy's law (Eq. 1):

$$\frac{Q}{A} = \frac{k_a}{\eta} * \rho_w g \frac{dh}{L} \qquad (1)$$

where Q is the volume of air measured at high pressure inlet side of soil (L^3T^{-1}); A is the cross-sectional area of core (L^2); η is dynamic viscosity of air ($ML^{-1}T^{-1}$); p_w is the density of water (ML^{-3}); g is acceleration due to gravity (LT^{-2}); dh is the pressure difference across soil core (L, difference in manometer reading) and L is the length of the soil core (L).

Methods

Methods of soil air permeability measurement can be broadly classified into two: steady and unsteady state methods. Steady state methods provide a direct measurement of k_a for known water content, which is assumed constant and uniformly distributed inside the soil sample during the entire experiment. In the unsteady state methods for k_a measurement, water content is not constant and calculations are made while the water content of soil is changing.

Steady State Method

The basic requirement for a steady state method for k_a measurement is that water content inside the soil core does not vary significantly during the experiments. Therefore, the steady state experiments must be performed over a short time duration in which the changes in water content should be assumed negligible. The other option is to use stationary liquid method, which involves air flowing upwards in response to the pressure gradient equal to that in the static liquid (Brooks and Corey, 1964; Corey, 1986). Figure 4 shows a schematic diagram of an Air Permeability apparatus for core samples, which is similar to that used by Brooks and Corey (1964) for disturbed soil samples. The apparatus essentially consists of a source of air supply, a small tubing for airflow, gaskets, a plexy glass system for holding the soil core, and a water manometer to measure pressure differential across the core.

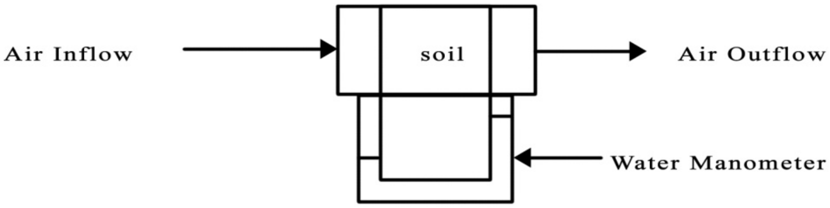

Figure 1. Schematic of the apparatus to measure air permeability (k_a).

In this laboratory exercise, we will use the same cores we used for retention curve measurement. At first we will equilibrate these cores to 60 cm suction. Subsequently we will place them inside the air permeability apparatus and using a method of constant gradient across the soil core we will calculate the air permeability of soil.

Procedure

1. Trim any excess soil so that the soil in the core occupies the entire volume of core. Weigh the core to one decimal place in g.
2. Cover the bottom of soil core with cheesecloth and place rubber bands around it to hold the cheesecloth. Weigh the core plus cheesecloth. Place core on a tray with cheesecloth end down and add water in the tray. Water level in the tray must not exceed the two-third height of the core.
3. Allow the cores to get saturated slowly. Never pour water on top of the soil core.
4. Desaturate the soil core by equilibrating over a tension table at 60 cm water suction. Weigh the core prior to the initiation of the experiment.
5. Place the soil core in the air permeameter, while making sure that the apparatus is airtight.
6. Start the airflow and measure the difference in the water level in the manometer once the flow achieves a steady state.
7. Remove he core from the permeameter and weigh it again to determine any change in soil water content.
8. Calculate the air permeability using equation 1.
9. Tabulate the data in a spreadsheet shown in Table 1.

10. Repeat the experiment at least 3 times for a higher airflow or manometer reading with the same soil core.
11. Repeat the experiment with other soil cores.
12. Compute mean and standard deviation of k_a based on three separate measurements.

References

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Practical 12: Prediction of soil hydraulic functions

Objective

In this lab we will use the water retention data obtained by using tension table and the pressure plate extraction methods, and will estimate the unsaturated hydraulic conductivity, diffusivity, and effective water content versus pressure head relationships. We will use the retention curve (RETC) program developed by van Genuchten et al. (1991) of Soil Salinity Lab, USDA, Riverside, California. We will also estimate unsaturated soil hydraulic functions with known values of van Genuchten model parameters.

Introduction

Accurate *in situ* measurement of the unsaturated hydraulic conductivity has remained especially cumbersome and a time-consuming procedure. An alternative to direct measurement of the unsaturated hydraulic conductivity is to use theoretical methods, which predict the conductivity from more easily measure soil water retention data. RETC computer program for describing the hydraulic properties of unsaturated soils is one such tool, which can be used to fit several analytical models to observed water retention and/or unsaturated hydraulic conductivity or soil diffusivity data. Some of the features in RETC are (i) a direct evaluation of they hydraulic functions when the model parameters are known, (ii) a more flexible choice of hydraulic parameters to be included in the parameter optimization process, (iii) the possibility of evaluating the model parameters from observed conductivity data rather than only from retention data, or simultaneously from measured retention and hydraulic conductivity data and (iv) user-friendly program preparation.

Parametric models for the soil hydraulic functions

Water flow in variably saturated soils is traditionally described by the Richards equation (Eq. 1)

$$C\frac{\partial h}{\partial t} - \frac{\partial}{\partial z\left(K\frac{\partial h}{\partial z} - K\right)} \qquad (1)$$

where h is the soil water pressure head (with dimension L), t is the time (T), z is the soil depth (L), K is the hydraulic conductivity (LT^{-1}), and C is the soil water capacity (L^{-1}) approximated by the slope (dθ/dh) of the soil water retention curve, θ(h), in which θ is the volumetric water content (L^3L^{-3}). The solution of the Richards equation requires knowledge of the unsaturated soil hydraulic functions (h) and K(h) or K(θ). The Richards equation in terms of water content of soil profile in homogenous and unsaturated (h<0) soil is of the following form (Eq. 2)

$$C\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z\left(D\frac{\partial\theta}{\partial z} - K\right)} \qquad (2)$$

where D, soil water diffusivity (L^2T^{-1}) is defined as per Eq. 3

$$D = K\frac{\partial h}{\partial\theta} \qquad (3)$$

The unsaturated soil hydraulic functions on these equations are soil water retention curve θ(h), the hydraulic conductivity function K(h) or K(θ), and the soil water diffusivity function D(θ).

Soil Water Retention Models

(a) Brooks and Corey (1964)

One of the most popular functions for describing θ(h) has been the equation of Brooks and Corey (1964), further referred to as the BC-equation (Eq. 4):

$$S_e = (\theta - \theta_r)/(\theta_s - \theta_r) \quad \{_1^{((\alpha h)^{(-\lambda)})} \quad _{(\alpha h \le 1)}^{(\alpha h > 1)}$$

(4)

where Se is the effective degree of saturation, also called the reduced water content (0<Se<1) θ_x and θ_s are the residual and saturated water contents, respectively; α is an empirical parameter (L^{-1}) whose inverse is often referred to as the air entry value or bubbling pressure, and λ is a pore-size distribution parameter affecting the slope of the retention function. For notational convenience, α and h are taken positive for unsaturated soils (i.e., h denotes suctions).

(b) van Genuchten (1980)

Several continuously differentiable (smooth) equations have been proposed to improve the description of soil water retention near saturation. A related smooth function with attractive properties is the equation of van Genuchten (1980), further referred to as the VG-equation (Eq. 5)

$$S_e = [1 + (\alpha h)^n]^{-m} \qquad (5)$$

where α, n, and m are empirical constants affecting the shape of the RETC. The limiting curve follows from equation (5) by removing the factor 1 from the denominator. This shows that the VG- and BC- functions become equivalent at low Se when λ = mn.

Hydraulic conductivity models

(a) Mualem's model

The model of Mualem (1976) for predicting the relative hydraulic conductivity, K, can be written as per Eqs. 6 and 7:

$$K(Se) = KsS_e^l\left(\frac{f(Se)}{f(1)}\right)^2 \qquad (6)$$

with

$$f(Se) = \int_0^{Se} \frac{1}{h(x)}dx \qquad (7)$$

where Ks is the hydraulic conductivity at saturation, and *l* is a pore-connectivity parameter established by Mualem (1976) to be about 0.5 as an average for many soils. Substituting the inverse of VG-equation into (6) then integrating and then substituting the k = 0 leads to the restriction m = 11 / n, and the equation 6 reduces to the following expression for K (Eq. 8):

$$K(Se) = KsS_e^{\frac{1}{2}}\left[1-\left(1-S_e^{\frac{1}{m}}\right)^{m}\right]^{2} \qquad (8)$$

In terms of pressure head

$$K(h) = \frac{Ks\{(1+\alpha h)^{mn}[1+(\alpha h)^{n}]^{-m}\}^{2}}{[1+(\alpha h)^{n}]^{ml}} \qquad (9)$$

For soil water diffusivity, the following equation can be derived from Equations (3) and (6):

$$D(Se) = \frac{(1-m)K_s Se^{l-\frac{1}{m}}}{\alpha m(\theta_s-\theta_r)\left[\left(1-Se^{\frac{1}{m}}\right)^{-m}+\left(1+Se^{\frac{1}{m}}\right)^{m}-2\right]} \qquad (10)$$

When the BC retention function is substituted into (6) the following hydraulic conductivity function with respect to water content, pressure head, and soil water diffusivity equations are obtained (Eqs. 11, 12, 13)

$$K(Se) = KsS_e^{l+2+\frac{2}{\lambda}} \qquad (11)$$

$$K(h) = \frac{Ks}{(\alpha h)^{\lambda l+2\lambda+2}} \qquad (12)$$

$$D(Se) = \frac{KsSe^{l+1+\frac{1}{\lambda}}}{\alpha\lambda(\theta_s-\theta_r)} \qquad (13)$$

The predictive equations for K used thus far assume that Ks is a well-defined and easily measured soil hydraulic parameter. This assumption is probably correct for many repacked, coarse-textured and other soils characterized by relatively narrow pore-size distributions. However, direct field measurement of Ks is generally very difficult for undisturbed and especially structured field soils. Also K near saturation is determined primarily by soil structural properties, which are subject to considerable spatial variability in the field. However, soil textural properties are less variable and have a more dominant effect on K in the dry range. The rapid decrease of the predicted K near saturation when n is relatively small in intuitively realistic. It suggests that K near saturation is determined by only a few very large macropores or cracks which may have little relation to the overall pore-size distribution that determines the general shape of the predicted conductivity curve at intermediate water contents. Thus, it seems more accurate to match the predicted and observed unsaturated hydraulic conductivity functions at water content somewhat less than saturation. The same holds for the θ_s, which is best regarded as an empirical parameter to be used in the context of a specific water retention model, and hence must be fitted to observed unsaturated soil water retention data points.

(b) Burdine's model

The model of Burdine (1953) can be written in a general form as given in Eqs 14 and 15:

$$K(Se) = Ks S_e^{l} \frac{g(Se)}{g(1)} \qquad (14)$$

where

$$f(Se) = \int_0^{Se} \frac{1}{[h(x)]^{-2}} dx \qquad (15)$$

as in Equation 6, the pore-connectivity parameter 1 accounts for the presence of a tortuous flow path. A variety of values have been suggested for l; Burdine (1953) assumed a value of 2. Results analogous to those for Mualem's model can be derived also for Burdine's model and can be referred in the User's manual for RETC code (van Genuchten et al., 1991).

Parameter estimation by RETC

The soil water retention curve, θ(h), according to (3) contains five potentially unknown parameters: θr, θs, α, n, and m. The predictive equation for K introduces l and Ks as two additional unknowns. Hence, soil hydraulic functions contain a maximum of seven independent parameters. The model parameters are represented here schematically by the parameter vector b = (θr, θs, α, n, m, l, Ks). The RETC code may be used to fit any one, several, or all of these parameters simultaneously to observed data.

RETC uses a nonlinear least-squares optimization approach to estimate the unknown model parameters from observed retention and/or conductivity or diffusivity data. The aim of the curve fitting process is to find an equation that maximizes the sum of squares associated with the model, while minimizing the residual sum of squares (SSQ). RETC provides additional statistical information about the fitted parameters such as r^2 mean, standard error, T-value, and lower and upper bounds of the 95% confidence level around each fitted parameter.

The Options in RETC application

The RETC code provides several options for describing or predicting the hydraulic properties of unsaturated soils. The code may be used to fit any one, several or all of the six or seven unknown parameters simultaneously to observed data. RETC can be applied to four broad classes of problems.

(1) **The direct (or forward) problem**: RETC may be used to calculate the unsaturated soil hydraulic functions if the model parameter vector b = (θr, θs, α, n, m, l, Ks) is specified by the user. Values for l and Ks are not needed when only the retention function is being calculated. The direct problem, which bypasses the optimization part of RETC, is being executed whenever this option is specified, or when no observed data are given in the input file.

(2) **Predicting K(h) from observed θ(h) data**: This option permits one to fit the unknown retention parameters (with or without restricted m, n values) to observed soil water

retention data. The fitted retention parameters are subsequently used to predict the hydraulic conductivity functions by making use of the models of Mualem or Burdine. This case assumes that the initial estimates for λ and Ks remain unaltered during the parameter optimization process.

(3) **Predicting θ(h) from K(h) data**: In some instances experimental conductivity data may be available but no observed retention data. RETC may then be used to fit the unknown hydraulic coefficients to observed conductivity data. Once the unknown coefficients are determined, the retention function may be calculated. This option is also needed when a consecutive fitting procedure is followed for the retention and hydraulic conductivity data, i.e., when some of the hydraulic parameters are first fitted to observed soil water retention data, followed by a fit of λ and/or Ks to observe conductivity data.

(4) **Simultaneous fit of θ(h) and K(h) data**: This option results in a simultaneous fit of the model parameters to observed water retention and hydraulic conductivity data.

Examples

The data in figure 1 a-b show an application of RETC, when 6 hydraulic parameters are fitted simultaneously to the observed retention (Abeele, 1979, 1984) and conductivity data. The analysis of these data was carried out for two cases. Case 1 fitted all the six unknown hydraulic parameters, θr, θs, α, n, l, and Ks. In case 2, the measured values of saturated water content θ_s and saturated conductivity Ks were used and remaining parameters were estimated.

A comparison of the estimated parameters in table 1 below shows that both cases produced similar results. The confidence intervals for l and Ks are wide, which indicates poor identifiably of these two parameters.

Parameter	Case 1	Case 2	Parameter	Case 1	Case 1
□r	0.026	0.045	*n*	1.474	1.636
□s	0.332	0.33*	*l*	0.495	-1.129
□	0.015	0.013	*Ks*	33.7	12.4*

The curves in Figure 2a were obtained by assuming that K, is known, thus forcing the theoretical and experimental conductivity functions (but not the diffusivity functions) to be matched at saturation. In Figure 2b the measured and predicted curves were matched at the point (θ_0, D_0) = (0.33, 0.0792 cm^2/s). The three calculated curves now match the data very well, except perhaps near saturation where the limiting diffusivity curve n-m underpredicts the observed values.

References

van Genuchten, M.Th. 1980. A closed form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci Soc Am J 44:892-898.

van Genuchten, M.Th., F.J. Leij, and S.R. Yates. 1991. The RETC code for quantifying the hydraulic functions unsaturated soils. Soil Salinity Lab, USDA, Riverside California.

Practical 13: Breakthrough curves

In this lab, we will conduct a displacement experiment, in which salt solution will displace water in a saturated soil column. The effluent solutions will be collected separately in small plastic bottles at a specific time interval. The electrical conductivity of these samples will be measured. Using inverse method, the measured breakthrough curve (BTC) will be fitted to one-dimensional convective dispersion equation (CDE) and various parameters of this equation will be obtained. Students will also use CXTFIT program to estimate solute transport parameters.

Basic Principle

The one-dimensional CDE for solute transport through porous media for nonsorbing solutes is the classical one-dimensional equation of Lapidus and Amundson, (1952) (Eq 1):

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} - v\frac{\partial C}{\partial x} \qquad (1)$$

where, R = 1 +$\rho K_D/\theta$; R is the retardation factor which takes into account linear and reversible equilibrium adsorption, θ is volumetric soil-water content (L^3L^{-3}), ρ is bulk density (ML^{-3}); K_D is the distribution coefficient (MM^{-1}); C is solution concentration (ML^{-3}); D is diffusion – dispersion coefficient (L^2T^{-1}); t is time (T); v is average pore water velocity (LT^{-1}); and x is distance (L). The apparent diffusion coefficient can be approximated by a BTC using the Eq.2 (Kirkham and Powers, 1972):

$$D = \frac{vL}{4\pi S^2} \tag{2}$$

where S is the slope of BTC at one pore volume $\left(\frac{\partial\left(\frac{C}{C_0}\right)}{\partial p}\bigg|_{p=1}\right)$.

According to Darcy's law the velocity of water (V_a) flowing through a unity cross section area (a) is proportional to the hydraulic gradient.

$$v_d \alpha . i \tag{3}$$

$$v_d = K . i \tag{4}$$

where K is the saturated hydraulic conductivity of soil (LT^{-1}), and i is the hydraulic gradient ($L\ L^{-1}$). The pore water velocity is given by the following expression

$$V = v_d/\theta, \tag{5}$$

where θ is the volumetric water content of soil (L^3L^{-3}).

Breakthrough curve

A plot of effluent solute concentration (or relative concentration) versus time or volume of effluent arrival, of the pore volumes known as BTC. The number of pore volumes (T_i) is calculated by dividing the amount of water (V_i) leached through the column in a given time interval (t_i) by the liquid capacity (volumetric water content) of the soil column (V_0=AθL), where A is the cross sectional area of the column, θ is the volumetric water content of the column, and L is the length of the column. The number pore volume can also be calculated by dividing the product of pore water velocity (v) and time interval (t) with length of soil column (L)

$T_i = V_i / V_0 = vt_i / L$

Plotting relative concentrations versus pore volumes generally facilitates the analysis of BTC. A typical example of BTC is given in the figure 1 below. In this study, bromide was displaced by chloride solution both for a step and pulse type application (Shukla et al, 2000).

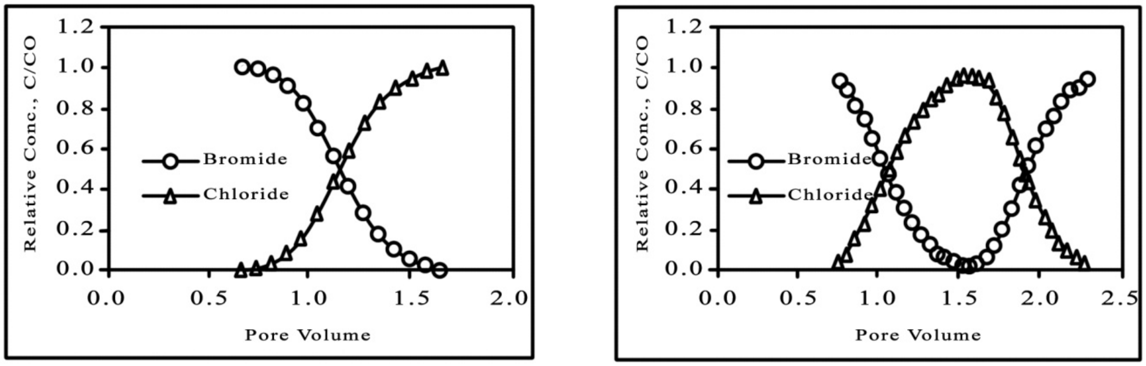

Figure 9.1. Breakthrought curves of chrloride and bromide for pulse type solute application.

Figure 9.1 presents BTCs of chloride and bromide when $MgCl_2$ solution displaces $CaBr_2$ solution for a step and pulse type of $MgCl_2$ application. The columns used for this displacement process were 10 cm long with 10 cm internal diameter and loam soil was packed in these columns. The bulk densities and water contents of these two soil columns were 1.43 $Mg.m^{-3}$, 1.48 $Mg.m^{-3}$, 0.44 mm^{-3} and 0.437 m m^{-3} respectively. These figures show that as more and more chloride enters the soil column, the chloride concentration in the effluent increases and corresponding bromide concentration decreases. In this study the effluent solutions were collected in plastic bottles. Table 1 explains how the relative concentration and pore volumes appearing in figure 1 were calculated.

The length of column (L) was 10 cm, volumetric water content (θv) was 0.44 and initial concentrations (C_0) of bromide and chloride were 6.9 and 3.6 mg L^{-1} respectively.

Area of cross section of soil column = $A = \pi * r^2 = 3.14*5^2 = 78.54$ cm^2

Average water velocity in the column = v_a = Last value in (2) / [last value in (1) * A]

= 572 / (32.5 * 78.54) = 0.22 cm h^{-1}

Average pore water velocity = $v = v_a / \theta v = 0.51$ cm h^{-1}

The volumetric water content of column = $V_0 = A \times \theta_v \times L = 78.54 \times 0.44 \times 10 = 345.6$ cm^3

Table 1. Sample calculations for pore volumes and relative concentration in figure 1a.

Time of effluent arriveal t_i (h) (1)	Volume of effluence V_i, (ml) (2)	Pore Volumes V_i/V_0 ml.ml^{-1} (3)=(2)/v_0	Pore Volumes vt_i/L (4)=v*(1)/10	Br Conc. MgL^{-1} (5)	Cl Conc. MgL^{-1} (6)	Relative Br Conc. (7)=(5)/6.9	Relative Cl Conc. (8)=(5)/3.6
13	223	0.645	0.664	6.90	0	1.000	0.000
14.5	249	0.721	0.741	6.83	0.04	0.990	0.011
19	327	0.946	0.971	5.68	0.57	0.824	0.159
23.5	407	1.178	1.201	2.86	2.13	0.415	0.591
26.5	461	1.334	1.354	1.25	3.01	0.182	0.835
32.5	572	1.655	1.661	0	3.60	0.000	1.000

Procedure

1. Weigh the empty plexy glass soil column assembly.
2. Place a filter paper or cheesecloth on lower end cap and place plexy glass column on the bottom end cap.
3. Start packing the soil by dropping 200 g of soil each time into it. Stir the soil inside the column with a thin rod to remove any layers formed during packing. Tap the column gently from all sides so that the column remains homogenous.
4. Once the soil is filled up to the top, place a filter paper or cheesecloth on the top, close column with plexy glass end cap and tight the screws.
5. Weigh the packed plexy glass assembly.
6. Start saturating the soil column with salt free water by slowly raising the head at the inlet.
7. Once the column is saturated, weigh.
8. Calculate the bulk density and water content (volumetric) of the soil column.
9. Raise the head at the inlet and collect effluent water for a given time interval. Calculate pore water velocity (volume of effluent collected/time interval/area cross-section of flow/volumetric water content). Adjust the head till you get the desired pore water velocity (q/θ).
10. Connect the inlet with salt solution of known concentration or conductivity. Start collecting the effluent sample in different bottles for a specific time interval.
11. After nearly 200 ml of salt solution is passed through the column, connect the input line back to the salt free water supply.

12. Continue collecting samples till you have collected at least 500 ml of effluent solution.
13. Measure the conductivity of samples, using conductivity meter.
14. Measure the volume of sample in each plastic bottle. Remember if time interval is constant then volume of effluent in the plastic bottle should also be constant.
15. Tabulate the data as given in table 2.
16. Calculate pore water velocity, pore volumes and relative concentration following the procedure used in table 1.
17. Plot the BTCs: (a) concentration (C) on Y-axis and volume of effluent collected on X-axis, (b) concentration (C) on Y-axis and time on X-axis and (c) relative concentration (C/C_0) on Y-axis and pore volumes (Vi/V_0) on X-axis. (Remember we displaced water with salt solution, therefore, we will get only one curve, which will be similar to chloride curve in figure 1).
18. From the figure obtained in (c) calculate the slope of BTC at pore volume equal to 1.
19. Calculate the dispersion coefficient using equation (2).

References

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Practical 14: Soil Shrinkage

If the volume of a soil containing clay is measured as it slowly dries, it is found that at high water contents for each unit of water lost the soil volume decreases by one unit and that the soil remains saturated (normal shrinkage). On further drying air begins to enter the voids and only a small amount of shrinkage takes place (residual shrinkage).

Agriculturally, shrinkage and volumetric changes are believed to contribute to the formation of soil structure as uneven stresses and strains develop on the soil mass. The bearing value of a soil increases as it dries out, hence the importance of shrinkage in relation to foundations and road construction. Shrinkage in very clayey soils also leads to the formation of deep and wide cracks, which influence soil-water movement, solute transport, and root growth.

Apparatus.

1. Evaporating Dish: a porcelain evaporating dish about 10 to 12 cm in diameter.
2. Spatula: a spatula or pill knife having a blade about 7-8 cm in length and 3 cm in width.

3. Shrinkage dish: a circular porcelain or metal dish having a flat bottom and being about 2 to 3 cm in diameter and 1 cm in height.
4. Micrometer to measure the dimensions of the soil pat.

Procedure

1. Prepare a semi-fluid paste of the assigned soil.
2. Weigh metal shrinkage dish (W_1).
3. Very lightly coat shrinkage dish with Vaseline.
4. Place one-third of the paste in the dish and tap the dish to remove air bubbles.
5. Add the second and third parts of the paste, tapping each time to avoid formation of air pockets.
6. Strike off excess paste to leave dish level full. Weigh the dish and contents (W_2).
7. To minimize the tendency for the soil to crack while drying, allow the soil to air dry for about 48 hours. After air-drying, dry the sample in the oven to a constant mass (m_3).
8. The capacity of the dish in cubic centimeters, which is also the volume of the wet soil pat, is to be determined by measuring with a Vernier Caliper.

Calculation of Water Content

The water content of the soil at the time it was placed in the dish expressed as a percentage mass of the dry mass of the soil is calculated as follows:

$$w = \frac{M_p - M_0}{M_0} * 100$$

where:

w = water content of the soil when placed in the dish (%),

Mp = mass of wet soil pat obtained by subtracting the mass of the shrinkage dish from the mass of the dish and wet pat [$W_2 – W_1$] and

M_0 = mass of dry soil pat obtained by subtracting the mass of the shrinkage dish from the mass of the dish and dry pat [$W_3 – W_1$].

Shrinkage Limit

The shrinkage limit of a soil is that water content, expressed as a percentage of the mass of the oven-dried soil, at which a reduction in water content will not cause a decrease in the volume of soil mass.

The shrinkage limit, S, is calculated from the data obtained in the volumetric shrinkage determination as follows:

$$S = w\left[\rho_w * \frac{(V - V_0)}{M_0}\right] * 100$$

where:

S = shrinkage limit

w = water content of wet soil, in percentage of the mass of oven-dried soil,

V = volume of wet soil pat,

V_0 = volume of dry soil pat,

M_0 = mass of oven-dried soil pat,

ρ_w = density of water (multiplication is necessary to balance units).

The volume of the dry soil pat is also determined by using the Vernier Calipers.

References

Marshall, T.J., J.W. Holmes, and C.W. Rose. 1996. Soil physics. Third Edition. Cambridge Univ. Press. p. 229-247.

Warkentin, B.P. 1993. Soil shrinkage. p. 513-518. *In* M.R. Carter (ed). Soil sampling and methods of analysis. Lewis Publishers, Boca Raton, FL.

Appendix C

PUBLISHED ARTICLES

MRCSP Phase II Publications			
Paper Cited	**Chapter Number(s)**	**Permission Cost ($)**	**Contact for Purchase**
Christopher, S.; Lal, R.; Mishra, U. 2009. Regional Study of No-Till Effects on Carbon Sequestration in the Midwestern United States. *Soil Science Society of America Journal*. Vol. 73, no. 1: 207-216.	3, 4	Free	For 365 days, but would prefer to post the abstract with a link to their website; Contact: Frances Katz fkatz@sciencesocieties.org
Blanco-Canqui, H.; Lal, R., 2008. No-tillage and soil-profile carbon sequestration: An on-farm assessment. *Soil Science Society of America Journal*. Vol. 72, no. 3: 693-701.	4	Free	For 365 days, but would prefer to post the abstract with a link to their website; Contact: Frances Katz fkatz@sciencesocieties.org
Chatterjee, A.; Lal, R. 2009. On farm assessment of tillage impact on soil carbon and associated soil quality parameters. *Soil & Tillage Research.* Vol. 104: 270-277.	4	36.99	http://www.copyright.com/
Christopher, S.F.; Lal, R. 2007. Nitrogen Management Affects Carbon Sequestration in North American Cropland Soils. *Critical Reviews in Plant Sciences.* Vol. 26: 45-64.	4	N/A	Not available to post on internet electronically
Mishra, U.; Ussiri, A. N. D.; Lal, R. 2010b. Tillage effects on soil organic carbon storage and dynamics in Corn Belt of Ohio USA. *Soil & Tillage Research.* Vol. 107: 88-96.	4	NA	Not available electronically

MRCSP Phase II Publications			
Paper Cited	**Chapter Number(s)**	**Permission Cost ($)**	**Contact for Purchase**
Blanco-Canqui, H.; Lal, R. 2007a. Impacts of long-term wheat straw management on soil hydraulic properties under no-tillage. *Soil Science Society of America Journal*. Vol. 71, no. 4: 1166-1173.	5	Free	For 365 days, but would prefer to post the abstract with a link to their website; Contact: Frances Katz fkatz@sciencesocieties.org
Blanco-Canqui, H., Lal, R. 2007b. Soil and crop response to harvesting corn residues for biofuel production. *Geoderma*. Vol. 141, no. 3-4: 355-362.	5, 6	N/A	Not available electronically
Blanco-Canqui, H.; Lal, R.; Post, W. M.; Owens, L. B. 2006a. Changes in long-term no-till corn growth and yield under different rates of stover mulch. *Agronomy Journal*. Vol. 98, no. 4: 1128-1136.	6	?	No reply
Blanco-Canqui, H.; Lal, R.; Post, W. M.; Izaurralde, R. C.; Owens, L. B. 2006b. Corn stover impacts on near-surface soil properties of no-till corn in Ohio. *Soil Science Society of America Journal*. Vol. 70, no. 1: 266-278.	6	Free	For 365 days, but would prefer to post the abstract with a link to their website; Contact: Frances Katz fkatz@sciencesocieties.org
Blanco-Canqui, H.; Lal, R.; Post, W. M.; Izaurralde, R. C.; Shipitalo, M. J. 2007a. Soil hydraulic properties influenced by corn stover removal from no-till corn in Ohio. *Soil & Tillage Research*. Vol. 92, no. 1-2: 144-155.	6	N/A	Not available to post on internet with out annual copyright license
Lal, R.; Pimentel, D. 2007. Biofuels from crop residues. *Soil & Tillage Research*. Vol. 93, no. 2: 237-238.	6	$17.25/ copy	http://www.copyright.com/

MRCSP Phase II Publications			
Paper Cited	**Chapter Number(s)**	**Permission Cost ($)**	**Contact for Purchase**
Stavi, I.; Lal, R.; Owens, L.B. 2010. Effects of Continuous No-till and Rotational Till No-till Practices on Soil Physical Characteristics in Eastern Ohio. Agronomy for Sustainable Development (in press)	7	?	No reply
Stavi, I.; Lal, R.; Owens, L.B. 2011. Effects of Cattle Grazing During the Dormant Season on hydrology and physical quality in a moist-temperate region. *Ecohydrology* 4:106-114	8	?	No reply
Tan, Z.; Lal, R.; Liu, S. 2006. Using experimental and geospatial data to estimate regional carbon sequestration potential under no-till management.. *Soil Science.* Vol. 171, no. 12: 950.	11	$12.79/copy	See invoice attached
Mishra, U.; Lal, R.; Slater, B.; Calhoun, F.; Liu, D.; Meirvenne, M. V. 2009. Predicting Soil Organic Carbon Stock Using Profile Depth Distribution Functions and Ordinary Kriging. *Soil Science Society of America Journal.* Vol. 73, no. 2: 614-621.	11	Free	For 365 days, but would prefer to post the abstract with a link to their website; Contact: Frances Katz fkatz@sciencesocieties.org
Mishra, U.; Lal, R.; Liu, D.; Meirvenne, M. V. 2010a. Predicting the Spatial Variation of the Soil Organic Carbon Pool at a Regional Scale. *Soil Science Society of America Journal.* Vol. 74: 906–914.	11	Free	For 365 days, but would prefer to post the abstract with a link to their website; Contact: Frances Katz fkatz@sciencesocieties.org