ABSTRACT

Title of Thesis: EVALUATION OF LABILE SOIL CARBON TEST FOR PREDICTION OF SOIL PRODUCTIVITY RESPONSE TO ORGANIC MATTER MANAGEMENT

Shawn T. Lucas, Master of Science, 2004

Thesis Directed by: Professor Ray R. Weil
Department of Natural Resource Sciences and Landscape Architecture

A $KMnO_4$ oxidation method for estimating labile soil C (C_L) was evaluated for use in a soil testing mode to identify soils where soil quality and productivity is likely or unlikely to respond positively to increased levels of C_L. Four sets of paired fields of the same soil series (within each set) but contrasting soil management history (continuous cropping vs. long-term sod) were studied. Fields with sod history initially tested higher in total soil C and C_L than fields with cropped management history. Within each field two treatments (winter rye cover crop or no cover crop) were applied in each of four blocks. Crop and soil functional responses to rye, when significant, were higher in fields that initially tested lower in C_L indicating that the $KMnO_4$ method used has some predictive value as a soil test. The method could be used in field testing kits for evaluation of soil C.

EVALUATION OF LABILE SOIL CARBON TEST FOR PREDICTION OF SOIL PRODUCTIVITY RESPONSE TO ORGANIC MATTER MANAGEMENT

by

Shawn Thomas Lucas

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park in partial fulfillment
of the requirements for the degree of
Master of Science
2004

Advisory Committee:

Professor Ray R. Weil, Chair
Professor Frank J. Coale, Member
Professor Robert J. Kratochvil, Member

TABLE OF CONTENTS

Section		Page
List of Tables		v
List of Figures		vi
Chapter One:	Relationships Between Biologically Active Soil Organic Matter and Soil Quality: Testing Labile Soil Carbon to Predict Soil Productivity Responses to Organic Matter Management.	
Literature Review		1
References		45
Chapter Two:	Labile Carbon Test for Predicting Response to Imroved Organic Matter Management. I: Crop Responses	
Introduction		57
Materials and Methods		64
Results and Discussion		77
Conclusions		85
References		86
Figures and Tables		93
Chapter Three:	Labile Soil Carbon Test to Predict Soil Response to Improved Organic Matter Management. II: Soil Function Responses	
Introduction		109
Materials and Methods		112
Results and Discussion		121
Conclusions		126
References		127
Figures and Tables		131
Chapter Four:	Effects of rye cover crops on soil quality indicators and crop productivity.	
Introduction		137
Materials and Methods		140
Results and Discussion		141

Conclusions 143
References 144
Figures and Tables 146

Appendix A: Field soil profile descriptions at Beltsville, Keedysville, Upper Marlboro and Holtwood 151

Appendix B: Field layouts at Beltsville. Keedysville, Upper Marlboro, and Holtwood 165

Appendix C: Analysis of systematic plot layout at Holtwood for non-random variation 170

Appendix D: Sample SYSTAT commands 178

Reference List: 182

LIST OF TABLES

Table Page

Table 2.1. Management history, soil series classification, taxonomic classification, initial pH, preliminary C_T (loss on ignition), and A horizon particle size analysis (by micropipette method) of the soils found contrastingly managed fields at four research sites.....93

Table 2.2. Range of characteristics observed in the soil profiles of fields having similar soils but contrasting management histories at four research sites.....94

Table 2.3. Field management histories at four research sites.....96

Table 2.4. Crop production schedules at four research sites for rye winter cover crops and subsequent summer crops.....97

Table 2.5. Rye and weed above- (Shoots) and belowground (Roots to 0-7.5cm depth) biomass means in 2002 and 2003 for each site.....99

Table 2.6. Mean dry stover yields of summer crops grown in 2002 and 2003.....100

Table 2.7. Mean dry grain yields of cash crops grown in 2002 and 2003.....101

Table 2.8. Mean dry total biomass yields of summer crops grown in 2002 and 2003....102

Table 2.9. Mean crop responses to cover crop treatment within fields of contrasting management history.....103

Table 2.10. Mean values for total C, total C / soil fine content (percent clay plus percent silt), $KMnO_4$ labile soil C, and $KMnO_4$ labile soil C / soil fine content in fields of contrasting management history at each research site.....104

Table 2.11. Correlations between relative cash crop responses to rye cover crops and soil C parameters across all sites, within Piedmont Province sites, and within Coastal Plain sites in 2002 and 2003.....106

Table 2.12. Correlations between cash crop responses to rye cover crops and soil C parameters at four sites in the Mid Atlantic region of the eastern U.S.....108

Table 3.1. Sitewise mean values for $C_{min\text{-}2d}$, N_{min}, and percent water stable aggregates in fields of contrasting management history and in cover crop treatment levels within these fields. The overall effects (across all sites) of field management history (FMH) nested within site and interaction between cover crop treatment and field management history nested within site are also presented.....131

Table 3.2. Mean soil function responses ($COVER_{rye}$ – $COVER_{bare}$) to cover crop treatment within fields of contrasting management history at three research sites.....132

Table 3.3. Correlations between soil functional responses to rye cover crops and soil C parameters across all sites, and within individual sites. In analyses across all sites, the response relationships are for relative responses (see Materials and Methods). At individual sites the response was related directly to measured soil C parameters.....135

Table 4.1. The effects of at least one year of winter cover crop treatments in eight experiments on cash crop stover, grain and total biomass production in 2002.....146

Table 4.2. The effects of two or more years of winter cover crop treatments in eight experiments on cash crop stover, grain and total biomass production in 2003.....147

Table 4.3. The effects winter cover crop treatments in eight experiments on soil C parameters.....148

Table 4.4. The effects winter cover crop treatments in six experiments on mineralizable N and percent water stable aggregates.....149

Table 4.5. Effects of one year and more than one year of winter cover crop treatments on crop productivity and soil quality parameters averaged across six experiments.....150

LIST OF FIGURES

Figure Page

Figure 2.1. Typical experimental field layout used at Beltsville, Keedysville, and Upper Marlboro.....95

Figure 2.2. Monthly precipitation levels and departures from normal for 2001, 2002, and 2003 at four research sites.....98

Figure 2.3. The relationship between total soil C content and labile soil C content in soils across four research sites. The Guassian bivariate confidence ellipse has P=0.6278 and *** indicates correlation is significant at P < 0.001.....105

Figure 2.4. The relationship between relative total biomass response to rye with labile soil C content in soils at two sites in the Piedmont physiographic region of the Mid-Atlantic U.S. The Guassian bivariate confidence ellipse has P=0.6278 and ** indicates correlation is significant at P < 0.01.....107

Figure 3.1. The relationships between C mineralized in 2 days (C_{min-2d}) and (A) total soil C, C_T and (B) labile soil C, C_L. Data are for soil sampled at three research sites after two years of rye cover crop treatments. The Guassian bivariate confidence ellipse has P=0.6278 and *** indicates correlation is significant at P < 0.001.....133

Figure 3.2. The relationships between mineralizable N (N_{min}) and (A) total soil C, C_T and (B) labile soil C, C_L. Data are for soil sampled at three research sites after two years of rye cover crop treatments. The Guassian bivariate confidence ellipse has P=0.6278 and *** indicates correlation is significant at P < 0.001.....134

Figure 3.3. The relationships between percent water stable soil aggregates (WSA) and (A) total soil C, C_T and (B) labile soil C, C_L. Data are for soil sampled at three research sites after two years of rye cover crop treatments. The Guassian bivariate confidence ellipse has P=0.6278 and *** indicates correlation is significant at P < 0.001.....135

CHAPTER ONE

Relationships Between Biologically Active Soil Organic Matter and Soil Quality: Testing Labile Soil Carbon to Predict Soil Productivity Responses to Organic Matter Management.

INTRODUCTION

Ecosystems and their associated environments are greatly affected by the quality of the air, water and soil that comprise them. While standards for water quality and air quality have been established, soil quality has not been easy to quantify (Doran and Parkin, 1994). The concept of soil quality refers to the suitability of a soil to perform specific ecosystem functions (Doran and Parkin, 1994; Bezdicek et al., 1996; Karlen et al., 1997; Karlen et al., 2001). In utilitarian terms soil quality is the compatibility between a soil's properties and a specific use (Gregorich et al, 1994). What constitutes a "good" soil depends on the purpose for which that soil is being used. In agroecosystems soil quality describes the fitness of a soil for the production of crops.

Interest in soil quality has grown as the sustainability of industrial agricultural systems has been questioned (Parr et al., 1992; Warkentin, 1995; Doran and Zeiss, 2000; Wander and Drinkwater, 2000). In the United States, and globally, soil quality has declined significantly since native, natural ecosystems such as grasslands and forests were cleared and cultivated for agricultural purposes (Doran and Parkin, 1994; Doran, 2002). Soil management practices used in agriculture are the primary reason for the declining soil quality (Lal, 1998a; Steer, 1998; Wander and Drinkwater, 2000; Doran, 2002; Lal et al., 2004). As a result of agricultural practices, soil has been physically lost through erosion and soil organic matter (SOM) contents have decreased significantly

(Houghton et al., 1983). In a little over half a century 2 billion of the roughly 8.7 billion ha of worldwide arable land, pastures, woodlands, and forests have been degraded (Steer, 1998). Lal (1998a) states that degradation and loss of agricultural land is one of humanity's most pressing ecological issues. This degradation of a valuable resource is compounded by the fact that the human population is projected to double over the next century (Ruttan, 1999). In order to maintain agricultural production and provide food for generations to come, the soil resource must be managed in a sustainable manner.

Assessing soil quality has been identified as a critical component of the sustainable management of agroecosystems (Larson and Pierce, 1994; Herrick, 2000; Doran, 2002). Sustainable management of an agroecosystem protects and enhances the soil while allowing land managers to maintain stable production and profits (Larson and Pierce, 1994). The physical, chemical, and biological properties of a soil dictate how that soil will function in an agroecosystem (Doran and Parkin, 1994). These properties exhibit great variation from soil to soil. For example, soil texture, a physical property, varies greatly between different soil types and can also vary spatially within the same soil by both depth and by gradients across a field. A chemical property such as CEC would also vary with the texture since it is highly influenced by clay content. Another chemical factor, pH can easily be changed through management. Biological properties, such as soil microbial biomass, can vary naturally by season and as a result of microclimatic changes (i.e., soil moisture) within a soil. The heterogeneous nature of soil prevents one from procedurally defining soil quality. It is not a directly measurable quantity, but must be inferred from measurable properties that are considered soil quality indicators (Acton and Padbury, 1993; Islam and Weil, 2000). Islam and Weil (2000) state that while

inherent soil properties, such as texture or parent material, may give one a general idea of a soil's quality, these properties are not useful as indicators ofsoil management effects on soil quality. Highly variable properties such as water content, field soil respiration, pH, and soil nutrient contents are not useful as soil quality indicators because they are subject to rapid change or can be routinely managed. However, dynamic properties that change at intermediate rates and show measurable effects due to management over several years are suitable for use as indicators of the effects of management on soil quality (Islam and Weil, 2000).

The role of soil organic matter in soil quality

Soil organic matter is considered a key determinant of soil quality (Larson and Pierce, 1991; Doran and Parkin, 1994; Sikora and Stott, 1996; Weil and Magdoff, 2004). The effects of SOM in soil are wide-ranging and affect soil biology, soil chemistry, and soil physical properties. Researchers have found that soil properties related to SOM can serve as important indicators of soil quality (Larson and Pierce, 1991; Arshad and Coen, 1992; Gregorich et al., 1994; Larson and Pierce, 1994; Kennedy and Papendick, 1995; Wander and Bollero, 1999; Ndiaye et al., 2000; Islam and Weil, 2000; Wander and Drinkwater, 2000).

The cation exchange capacity (CEC) of a soil affects the nutrient holding capacity of a soil as well as the effectiveness (and removal from the soil solution) of applied pesticides. A soil's CEC is partially determined by the SOM content of that soil (Heil and Sposito, 1997; Brady and Weil, 2002). The cycling of carbon and major plant nutrients (particularly nitrogen, sulfur, and phosphorus) through SOM has been well

documented (Stevenson and Cole, 1999). Upon decomposition by microbes, SOM releases plant available forms of the nutrients into the soil ecosystem (Heil and Sposito, 1997; Christensen and Johnston, 1997). Biological activity in soils is related to SOM content in that the decomposable fractions of SOM serve as the substrate for the flora and fauna found in a particular soil ecosystem (Tabatabi, 1996; Weil and Magdoff, 2004). In many soils SOM is the dominant factor in the binding of soil aggregates. These aggregates are the basis of soil structure in most topsoils (Tisdall and Oades, 1982). Soil structure in turn plays a large role in soil bulk density, soil porosity, soil water dynamics (such as infiltration and water holding capacity) and soil erosion potential (Tisdall and Oades, 1982; Gregorich et al., 1994; Weil and Magdoff, 2004). In addition SOM influences sorption of organic compounds (via CEC), sorption of anions, pH buffering capacity, and mobility of metals within a soil (Weil and Magdoff, 2004).

Soil organic matter defined

Much like definitions of soil quality or sustainable management, the definition of soil organic matter differs depending on the definer. Soil organic matter is "the organic fraction of soil exclusive of undecayed plant and animal residue" as defined by the Soil Science Society of America, 2001. Since many laboratory procedures fail to differentiate between decayed and non-decayed plant and animal tissue that pass a 2-mm sieve (Sikora and Stott, 1996) a broader definition of SOM is more appropriate. According to Magdoff (1992) "SOM consists of diverse components such as living organisms, slightly altered plant an animal organic residues, and well-decomposed organic residues that vary considerably in their stability and susceptibility to further decomposition." In a similar

definition, Brady and Weil (2002) describe SOM as "The organic fraction of the soil that includes plant and animal residues at various stages of decomposition, cells and tissues of soil organisms, and substances synthesized by the soil population."

The soil microbial biomass plays a significant role in SOM dynamics (Magdoff, 1996; Weil and Magdoff, 2004). It seems logical to include the living microflora and microfauna as part of SOM because these organisms are intimately bound to the decomposing materials and have a direct influence on the dynamics and physical state of organic materials in the soil. In addition, chemical or physical laboratory tests for SOM certainly kill these organisms and subsequently oxidize, extract, or combust their organic components. Given that assessment of soil quality so often depends on evaluations of recently deposited, partially decomposed detritus, active materials, as well as the living biomass, it seems appropriate to use a definition for SOM that encompasses these factors when discussing soil quality as a function of SOM. For the purposes of this manuscript SOM will be defined according to a modified version of the Brady and Weil (2002) definition: The organic fraction of the soil that includes plant and animal residues at various stages of decomposition, cells and tissues of soil organisms, and substances synthesized by the soil population, and the microflora and microfauna actively involved in utilization of these decomposing materials.

Heterogeneous composition of soil organic matter: Soil organic matter pools

Soil organic matter is an extremely variable and complex constituent of soils. The content and chemical make-up of SOM is not completely understood but models attempting to classify SOM components have been established. Classification of SOM

components is important because different components can have distinct effects on the behavior of a soil in an agroecosystem (Magdoff, 1996). The most common method of classifying the components that make up SOM in a soil is by pooling them based on their rate and/or degree of decomposition (Jenkinson and Rayner, 1977; McGill et al., 1981; Parton et al., 1987; Paustian et al., 1992; Magdoff, 1996; Weil and Magdoff, 2004). The number of pools varies from model to model. McGill et al. (1981) described ten discrete pools, however more commonly cited models describe two (Duxbury et al., 1989; Hsieh, 1992) or three (Jenkinson and Rayner, 1977; Parton et al., 1987) SOM pools.

The models described by Jenkinson and Rayner (1977) and Parton et al. (1987) have relative agreement between their estimates of mineralization rates and decomposition rates within each SOM pool. Parton et al. (1987) classify SOM, based on decomposition turnover times, into an active pool, a slow pool, and a passive pool. In the Parton et al. (1987) model, the active pool is made up of easily decomposable, or labile, materials. Active pool constituents have a very short turnover time, decaying in a timeframe of months to a few years. Organic compounds forming the slow pool occur in chemical forms that are somewhat resistant to biological degradation. Slow pool compounds have also been described as being physically protected from degradation (ie. via sequestration in soil aggregates) (Paul and Van Veen, 1978). Biological turnover in the slow pool is on the order of 20-40 years and the C:N ratio of this pool is estimated to be on the order of 12 to 20 (Parton et al., 1987). According to Parton et al. (1987) the passive pool is comprised of highly decomposed, chemically recalcitrant, humic compounds. Compounds in this pool may also be physically protected. Turnover rates of

passive pool substances are estimated to be anywhere from 200-1500 (or more) years with a C:N ratio estimated at 11 to 12 (Parton et al., 1987).

The three-pool CENTURY model described by Parton et al. (1987) is a mathematical modeldesigned to simulate the effects of climatic gradients on SOM and productivity. When discussing soil quality it may be more practical to classify into two conceptual pools: one that is labile or highly decomposable (an active pool) and a second that is inert or stable (a passive pool). Duxbury et al. (1989) and Hsieh (1992) have described SOM in these terms.

The passive pool, due to its recalcitrant nature, tends to slowly accumulate throughout time. As a result this pool contains the bulk of organic C found in soils (Janzen et al., 1997; Weil and Magdoff, 2004). The passive pool provides the bulk of a soil's SOM-derived CEC (Magdoff, 1996). This pool changes very little in ecological time frames and is only slowly affected by agricultural management practices (Janzen et al., 1997).

The active pool of SOM forms a relatively small portion of total SOM but it plays important roles in maintaining and monitoring soil quality (Gregorich et al., 1994; Janzen et al., 1997; Weil and Magdoff, 2004). This pool is comprised of materials in transition from fresh detritus to stable humic compounds (of the passive pool) or microbially respired CO_2 (Janzen et al., 1997). The labile nature of active pool SOM makes it sensitive to various soil management and cropping practices (Biederbeck et al., 1994; Gregorich et al., 1994; Magdoff, 1996; Weil and Magdoff, 2004).

The various conceptual SOM pools are allinterrelated. As the livi ng organisms metabolize active pool SOM, they respire some of the substrate off as CO_2, and they also

excrete recalcitrant degraded byproducts of substrate C that become part of that passive pool (Magdoff, 1996).

A closer look at active pool soil organic matter

According to the SOM models proposed by Parton et al. (1987) and Paustian et al. (1992), the active pool of SOM consists of live microbes and microbial products as well as recently deposited, readily mineralizable organic residues. Other active pool components include amino acids, simple sugars, polysaccharides, microbially synthesized biochemicals, and exudates from plant roots (Weil and Magdoff, 2004; Wander, 2004). The key to the active pool is that all of its constituents have a short turnover time in the soil. In general the estimated turnover time of the active pool is on the order of 1-5 years (Parton et al., 1987), however some active pool components, such as the easily metabolized portions of recently deposited organic materials can be utilized by the microbial biomass within months (Mcgill et al., 1981). Likewise the microbial biomass itself turns over in less than a year (Paul, 1984).

The easily metabolized substances that make up the active pool provide the fuel for the living biomass and thus drive nutrient cycling in soils. The nature of organic residues that are deposited on a soil plays a role in determination of the microbial diversity within that soil (Bradford et al., 2002), which in turn can have an effect on soil functions such as biological control of plant pests, disease suppression, and nutrient cycling. Active pool SOM is directly related to mineralization and availability of soil C, N (Alvarez et al., 1998b; Gunapala and Scow, 1998), S (Banerjee and Chapman, 1996), and P (Jenkinson and Ladd, 1981; Marumoto et al., 1982).

Incompletely humified organic material has a binding effect on soil particles (Buyanovsky et al., 1994) that contributes to stabilization of soil structure (Tisdall and Oades, 1982). Aggregate stabilization is also facilitated by polysaccharides excreted by roots and microbes (Angers and Mehuys, 1989; Cheshire et al., 1989; Martens and Frankenberger, 1992). This stabilization occurs through cation bridging, as polysaccharides adsorb to negative charges on soil particles (Chenu, 1995). Other active pool components that have a binding effect, according to Buyanovsky et al. (1994), are root hairs and fungi. Due to its association with aggregate stability the active pool of soil organic C also plays a role in the infiltration rate of soils (Bell et al., 1998; Bell et al., 1999). Well-aggregated soils that are resistant to slaking in water have higher infiltration rates (Rasiah and Kay, 1995; Morin and van Winkel, 1996). In addition this resistance to slaking provides a well-aggregated soil with more persistent structure, minimizing surface crusting (Pagliai and Antisari, 1993).

Assessing soil organic matter as an indicator of soil quality

The complex, variable, and reactive properties of SOM make its assessment a challenge. There is no laboratory test to directly quantify SOM. Estimation of SOM is usually accomplished through a measure of soil organic carbon (SOC), total soil carbon, or weight loss on ignition (Tabatabai, 1996; Weil and Magdoff, 2004). Various methods exist to estimate SOM, but all have limitations and inherent sources of error. Comparing results determined by different methods or different labs can be difficult; different methods often do not yield comparable results, nor are they completely standardized from lab to lab (Lal et al., 2001; Weil and Magdoff, 2004). Common methods used to estimate

SOM are the Walkley-Black wet chromate oxidation in strong acid (Walkley and Black, 1947) and the weight loss on ignition method. These analyses attempt to provide an estimate of total SOM and are useful to farmers when they need to modify N fertilizer recommendations or apply lime or pesticides. However, total SOM is not a good measure of management-induced change in soil quality because the bulk of total SOM is recalcitrant passive pool material. The slow rate of change of these materials renders total SOM impractical for rapid assessments of soil quality changes.

When assessing soil quality for the purpose of determining sustainable best management practices, useful indicators are ones that exhibit sensitivity to management practices. While no single measurement that encompasses the entire active pool exists, various measurements that provide estimates of the active pool have shown some degree of sensitivity in short time frames to soil management practices (Biederbeck et al., 1994; Gregorich et al., 1994; Magdoff, 1996; Weil and Magdoff, 2004).

Active pool soil organic matter as an indicator of soil quality

Various parameters related to the active pool of SOM have been used in soil quality assessments. The approaches taken in these assessments are numerous and often are not standardized. This can make comparing data generated by different research groups or different studies challenging. Active pool estimations have been based on physical fractionation and characterization of organic debris, chemical extraction, and indicators of soil biological activity.

Among the most commonly used methodologies to assess active pool materials are those based on dispersing soils and physically separating loose organic debris that is

not intimately associated with soil mineral colloids. This can be achieved by density separation in a liquid, with floating organic materials being collected, measured, and referred to as the light fraction (LF) (Christensen, 1992; Wander et al., 1994; Alvarez et al.; 1998b). Another physical fractionation method involves isolating particulate organic matter (POM) by sieving out particles larger than 53μm and subsequently separating sand from organic debris (Cambardella and Elliot, 1992; Wander et al., 1998; Needelman et al., 1999). Sometimes the density and sieving methods are combined (Cambardella and Elliot, 1993a; Wander and Yang; 2000). Wander (2004) notes that various incarnations of these physical separation methods are increasingly being used as a measure of labile SOM because they readily show SOM response to soil management. The use of these physical fractionations is limited in that, while they are most often used as indicators of labile SOM, LF and POM are heterogeneous mixtures of organic materials, some of which can be associated with the slow and passive pools of SOM (Wander, 2004). Thus additional separations must be performed to characterize these components. Another drawback is that LF and POM are laboratory-derived measurements and the relationships between their characteristics and soil processes at the field level have not been clearly determined (Wander, 2004). Despite the limitations LF (Christensen, 1992; Wander et al, 1994) and POM (Cambardella and Elliot, 1992; Wander et al, 1998, Needleman et al, 1999) seem to offer promise as soil quality indicators that will indicate probable direction of SOM change due to soil management such as tillage or type of farm system (organic vs. conventional).

Soil aggregate stability is a physical soil parameter (which relies on biological and chemical processes and interactions) that has been associated with active pool SOM.

According to the hierarchical model developed by Tisdall and Oades (1982) soil aggregates can be classified by size. In this model aggregates greater than 250μm in diameter are referred to as macroaggregates, while microaggregates are less than 250μm in diameter. Macroaggregates generally have higher levels of organic matter than microaggregates (Dormaar, 1983) and macroaggregate associated organic matter is more labile than that found in microaggregates (Elliott, 1986; Gupta and Germida, 1988; Buyanovsky et al., 1994). There is evidence to indicate that macroaggregates form around recently deposited POM (Cambardella and Elliot, 1993b). Buyanovsky et al. (1994) found macroaggregates to be enriched in C when compared to whole soil and this C was in the form of relatively labile plant fragments. In microaggregates, which are not destroyed by tillage, interaction between clay and SOM renders the organic substances somewhat protected from decomposition (Tisdall and Oades, 1982). Examples of the relationships between aggregate stability and management practices are discussed in subsequent sections.

Many estimates of biological activity have been used as indicators of active pool SOM. Among these estimates are measurements of microbial biomass itself, microbial biomass C, microbial biomass N, basal respiration, mineralizable C, mineralizable N, and soil enzyme activity (Gregorich et al, 1994). Among the drawbacks of these methods (aside from standardization issues), is that several of them (microbial biomass C, microbial biomass N, basal respiration, mineralizable C, and mineralizable N) require long incubations and time consuming analyses. In addition, some common methods for microbial biomass (Jenkinson and Powlson, 1976) microbial biomass C (Vance et al., 1987; Jenkinson, 1988), and microbial biomass N (Jenkinson, 1988) require the use of a

hazardous chloroform fumigation step to lyse microbial cells. Gregorich et al. (1994) have done an extensive review of these parameters and provide references to procedural manuscripts and parameter sensitivity to management practices.

Of the above-mentioned biological indicators of active pool SOM, mineralizable N and mineralizable C are among the more commonly used methods (along with microbial biomass N and microbial biomass C). Gregorich et al. (1994) define mineralizable N and mineralizable C as the portions of SOC and soil organic N that can be readily decomposed. These soil N and C pools are important because mineralizable C provides much of the substrate C that drives microbiological processes in the soil, while mineralizable N is incorporated into microbial cellular components such as amino acids, enzymes (used in decomposition processes), proteins, and DNA. Much of the mineralized C is respired as CO_2 while the mineralized N is released into the soil in plant available forms as the microbial population turns over. Examples of mineralizable C and mineralizable N sensitivity to management practices are discussed in more detail in subsequent sections.

Chemical extraction techniques to estimate active pool SOM include various methods using water to extract a labile fraction of SOC (McGill et al., 1986; Davidson et al., 1987; DeLuca and Keeney, 1994; Zsolnay and Gorlitz, 1994; Sparling et al., 1998). Sparling et al. (1998) demonstrated that hot-water extracts have a close relationship to microbial biomass C. This relationship seems logical given that the method was designed keeping in mind the temperature (70°C) (temperature from Stanier et al., 1968, cited in Sparling et al., 1998) at which vegetative microbial cells are killed while not using too hot an extractant that would cause non-microbial organic C to be solubilized. Labile C

extracted with cold-water methods may not represent C from the microbial biomass (DeLuca and Keeney, 1994). Water-soluble C methods have been shown to be sensitive to management practices such as tillage and nitrogen treatments (Liang et al., 1998) or land use (arable vs. pastoral) (Haynes, 2000).

A promising, management sensitive, chemical extraction method recently developed by Weil et al. (2003) estimates active pool C by oxidizing labile C with a dilute (0.02M) potassium permanganate ($KMnO_4$) solution. This method is rapid, easy to perform, and $KMnO_4$ is a relatively safe working reagent. This method will be discussed in detail in the following section.

Potassium permanganate oxidized C as an indicator of active pool C

Weil et al. (2003) have noted that there is a growing need for simple, rapid methods to assess soil quality in the field and in laboratories. Such methods could be included in a soil quality test kit such as that currently available from the NRCS (USDA-NRCS, 1998). Few, if any, of the active pool assessment methods described above are suited for simple, rapid estimation of a soil's active pool SOM content. In addition standardized methods have not been agreed upon for many of active pool indicators previously discussed.

Recently a method for quantifying active soil organic C, the potassium permanganate ($KMnO_4$) oxidizable C test, has been developed. This method involves oxidizing labile organic C by exposing it to a known concentration of $KMnO_4$ and subsequently measuring via spectrophotometer the change in $KMnO_4$ concentration due

to reaction with labile soil C (Lefroy et al., 1993; Blair et al., 1995; Moody et al., 1997; Bell et al., 1999; Weil et al., 2003).

Under alkaline conditions $KMnO_4$ acts as a strong oxidizer. This is due to the large negative potential between Mn^{2+} and MnO_4^- ions (Cotton and Wilkinson, 1965). Loginow et al. (1987) demonstrated that at pH 7.2, $KMnO_4$ oxidized components of SOC. The oxidation reaction resulted in a decrease in $KMnO_4$ concentration that could be measured colorimetrically via spectrophotometer. Among the compounds affected by $KMnO_4$ are C-compounds containing hydroxyl, ketone, and/or carboxyl, double bond linkages, aliphatic compounds, simple carbohydrates, amino acids, amine sugars and amide sugars (Skoog and West, 1969; Stanford, 1978; Loginow et al. 1987). Loginow et al. (1987) used 0.033M, 0.167M and 0.333M $KMnO_4$ to fractionate SOC based on susceptibility to oxidation. Lefroy et al. (1993) used the same concentrations and attempted to relate the associated SOC fractions with soil quality properties such as infiltration and aggregation. Based on the conclusion reached by Lefroy et al. (1993) that 0.333M $KMnO_4$ sufficiently characterized the labile portion of SOC, Blair et al. (1995) used measurements of 0.333M $KMnO_4$ oxidizable SOC and total SOC (measured by loss on ignition) to calculate two fractions of SOC: one that was oxidized by $KMnO_4$ and a second fraction that remained unaffected by $KMnO_4$. Blair et al. (1995) used this method to compare arable soils to adjacent undisturbed "reference sites" and through this comparison they developed a C management index (CMI).

The $KMnO_4$ method described in Blair et al. (1995) appears to react with a relatively labile pool of SOC and shows more sensitivity to management practices, such as crop rotations and fallow periods, than does total SOC (Blair and Crocker, 2000;

Whitbread et al., 2000; Blair et al., 2001). Bell et al. (1998) and Bell et al. (1999) used the Blair et al. (1995) method to correlate $KMnO_4$ oxidizable C with aggregate stability and infiltration. Whitbread et al., (2000) also saw a relationship with aggregate stability. Bell et al. (1998) and Moody et al. (1997) observed a relationship between this SOC fraction and effective CEC. Potassium permanganate oxidizable C measurements have shown higher levels of labile C in undisturbed soils under grass when compared to arable soils (Lefroy et al., 1993; Blair et al., 1995; Bell et al., 1998; Bell et al., 1999).

While the size of the active pool of SOC varies from soil to soil it is generally considered to be but a small fraction of total SOC (Parton et. al, 1987; Magdoff, 1996, Weil and Magdoff, 2004). Parton and Rasmussen (1994) used 2-5% of total SOM as an estimate of active pool SOM in CENTURY model simulations of SOM dynamics. Blair et al. (1995) calculated that the SOC fraction oxidized by 0.333M $KMnO_4$ in their method reacted with 14-27% of the total SOC in the 13 Australian soils tested. This seems to indicate that more than just the most labile fractions of SOC are being oxidized when 0.333M $KMnO_4$ is used. Further evidence of this is seen in a study by Khanna et al. (2001) thatmeasured labile SOC by the Blair et a l. (1995) method in six forest soils. Khanna et al. (2001) measured labile C in the soils before and after incubation at 20˚C. They also trapped CO_2 respired during the incubation. In this experiment there was no consistent relationship between post-incubation 0.333M $KMnO_4$ oxidizable C and levels of CO_2 respired during incubation.

Weil et al. (2003) hypothesized that labile SOC fractions associated with soil quality might better be represented by more dilute concentrations of $KMnO_4$. This was based on the fact that in Lefroy et al. (1993), three of four cases testing the effects of

long-term conventional tillage showed a larger decline in 0.033M $KMnO_4$ oxidizable C than in C oxidized by the 0.333M reagent. Weil et al. (2003) also note that while Bell et al. (1998) saw relationships between 0.333M $KMnO_4$ oxidizable C and soil properties associated with soil quality (aggregate stability, infiltration rates, and effective CEC), these soil properties had a higher degree of correlation with 0.033M $KMnO_4$.

Weil et al. (2003) developed a modified $KMnO_4$ method using a 0.02M solution based on the observations that a more dilute solution was more sensitive to management practices and more closely correlated with soil quality parameters. The more dilute solution was also easier to prepare than the 0.333M reagent, in which $KMnO_4$ does not easily go completely into solution. The Blair et al. (1995) method was further modified by adding 0.1M $CaCl_2$ to the permanganate reagent. This obviated the need for a centrifugation step in the procedure by causing flocculation and subsequent rapid settling of soil particles, thus making the procedure more suitable for use in a field kit.

Among the limitations of the $KMnO_4$ oxidation methods is the somewhat vague understanding of the chemistry involved in the reaction of MnO_4^- with SOC. The nature of the oxidized C has come into question and the rates of the oxidative reaction are not well understood (Tirol-Padre and Ladha, 2004). Tirol-Padre and Ladha (2004) tested several substances that $KMnO_4$ theoretically should have readily oxidized, and found that they were either slowly oxidized (sugars, amino acids, and other organic acids) or not oxidized at all (cellulose). They also reported that $KMnO_4$ did not seem to discriminate between labile and nonlabile SOC and they found little correlation with microbial biomass C. Tirol-Padre and Ladha (2004) suggested that $KMnO_4$ oxidized C should be referred to as permanganate oxidizable C (POC) as opposed to labile C.

Others have also noted that $KMnO_4$ oxidation of soil C is not a fully elucidated process. Shang and Tiessen (1997) oxidized soils with 0.033M $KMnO_4$ and measured pre- and post-oxidation total SOC in the same soils by the loss on ignition method. They found that $KMnO_4$ labile C measured colorimetrically was much less than the difference between pre- and post-oxidation total SOC measured by loss on ignition. They suggested that this difference might in some way be due to interference with $KMnO_4$ absorbance in the sample supernatant. They did find that oxidation with 0.033M $KMnO_4$ was able to detect a decrease in labile C in cultivated soils when they were compared to neighboring soils that were historically undisturbed.

When assessing the limits of $KMnO_4$ oxidizable C as an indicator of labile soil C as presented by Shang and Tiessen (1997) and Tirol-Padre and Ladha (2004) it should be noted that these evaluations were performed at 0.033M $KMnO_4$, a somewhat higher concentration than the 0.02M solution used in the Weil et al. (2003) method. Weil et al. (2003) found that using solutions stronger than 0.025M created larger standard errors and reduced the ability of statistical ANOVA to discern management induced differences. In addition, Weil et al. (2003) found measurements made with 0.02M $KMnO_4$ to be strongly correlated with microbial biomass C. The microbial biomass C measurements made by Tirol-Padre and Ladha (2004) only used 8 poorly drained soils, all from rice fields, while microbial biomass C measurements described in Weil et al. (2003) were made in 18 soils that covered a wide range of textures, drainage classes, SOM content, and management systems. The small sample size and limited range of soils, combined with higher standard errors resulting from the use of a higher $KMnO_4$ concentration, could be behind the lack of a relationship between $KMnO_4$ oxidized C and microbial biomass C seen in

Tirol-Padre and Ladha (2004). It may also be the case that the C in the rice field soils used by Tirol-Padre and Ladha could have undergone anaerobic decomposition. Rates and products of decomposition of plant residues in anaerobic systems may be different than those observed in well-drained upland soils. Weil (unpublished data) noted that some poorly drained soils in the Weil et al. (2003) study may have been outliers in an otherwise close relationship between microbial biomass C and $KMnO_4$ oxidizable C. Additional study on the differences of $KMnO_4$ oxidizable C between well-drained and poorly drained soils should be conducted. The nature of MnO_4^- reactions with SOC is not well understood, yet there seems to be strong relationship seen with microbial biomass C (and other microbial activity indicators) as seen in Weil et al. (2003). Further research into the mechanisms of $KMnO_4$ reactions with SOC needs to be performed.

In addition, more study of the relationships between the soil microbial biomass and $KMnO_4$ may also be warranted. A potentially interesting study would be to repeat the study by Khanna et al. (2001) using the methods of Weil et al. (2003). Another potential study aimed at more directly discerning relationships between the microbial biomass and $KMnO_4$ oxidizable C might involve killing the microbial biomass via fumigation (as in Vance et al., 1987) or irradiation (as in Islam and Weil, 1998) and subsequently measuring $KMnO_4$ oxidizable C in the treated soil as well as a sample in which the biomass is intact.

While permanganate chemistry may not be totally clear, the Weil et al. (2003) $KMnO_4$ oxidizable C method seems specific for some labile fraction of SOC and does not seem to affect the more humified carbonaceous substances associated with the slow and passive fractions of SOM. It was shown to be more sensitive to management effects

(tillage treatments) than total SOC and Weil et al. (2003) found it to be more closely correlated with other soil quality indicators (measures of microbial activity [including microbial biomass, microbial biomass C, basal respiration, and others] and aggregate stability) than total SOC. They suggest that this method is a simple, repeatable means to estimate a biologically active C pool that is associated with soil quality. Most practically, due to its ease of use and sensitivity to soil management practices, this method, through verifying or predicting soil quality changes due to management, could aid farmers in their soil management decisions.

Soil Organic Matter Dynamics I: Natural processes

The SOM content of a soil is dynamic in nature. A soil's SOM content is a function of additions and losses occurring through time (Magdoff, 1996). Changes in SOM on an annual basis can be represented mathematically as:

$$\Delta SOM = additions - losses$$

To a large degree a soil's capacity to accumulate SOM is determined by natural environmental factors: landscape, texture, and climate. (Dick and Gregorich, 2004). If left to these natural factors SOM tends toward some equilibrium (different from soil to soil) where:

$$additions = losses$$

The additions in a system are mainly the result of primary production (annual plant productivity) and decomposition of detritus, while losses are the result of the mineralization of SOM and subsequent respiration, uptake, leaching, or removal by other

processes, of those mineralized compounds (Magdoff, 1996; Janzen et al., 1997; Weil and Magdoff, 2004; Magdoff and Weil, 2004).

The natural environmental factors play various roles in SOM dynamics. Not surprisingly, given the processes behind additions and losses of SOM, climate plays a major role in SOM content. Climate, specifically temperature, precipitation, and solar radiation, will greatly affect the rate of primary production as well as the rate of the micobial activity by which decomposition and mineralization occur (Weil and Magdoff, 2004; Dick and Gregorich; 2004). Landscape position tends to affect SOM through microclimatic influence along with translocations from upper slope positions to toeslope positions (Dick and Gregorich; 2004). Texture affects SOM levels in a soil in that finer textured soils tend to accumulate more SOM (Jenkinson and Rayner, 1977). This is due to a variety of mechanisms that include the effects of smaller pores on oxygen and water supplies (which affect decompostion rates), chemical adsorption to clays (Dick and Gregorich; 2004), and physical protection in aggregates that form more readily in finer textured soils (Six et al., 2002). These natural environmental factors form the foundation for a soil's capacity to accumulate SOM; for practical purposes, however, these environmental factors are independent of human activity.

Soil organic matter dynamics II: Human influences.

One could argue that global warming, massive site grading, and incorporating truckloads of sand into a soil are human influences on climate, landscape, and texture, respectively. In agricultural systems, however, managing these environmental factors is not generally feasible. In contrast to unmanageable natural factors that affect SOM

content, human controlled factors such as soil inputs and disturbance also affect SOM (Dick and Gregorich, 2004).

Organic inputs affecting SOM content include aboveground crop residues, crop roots, animal manures, processed biosolids (sewage sludge), composts, and other organic materials deposited in or on the soil (Dick and Gregorich, 2004). In agricultural systems, non-organic inputs such as nitrogen fertilizer applications can also affect SOM by increasing net primary production (Paustian et al., 1997a). Fallow periods are also a type of input management. While many input management schemes increase SOM, fallow systems have been shown to decrease SOM content when compared to continuous cropping (Unger, 1982; Rasmussen and Parton, 1994). This result in fallow systems is due the fact that, during fallow periods, the primary production is virtually nonexistent while oxidation of SOM can actually increase (Rasmussen and Parton, 1994). Specific inputs, management practices and SOM implications are discussed below.

Disturbance events can also affect SOM levels and can be caused, influenced or prevented by management activity. While inputs tend to increase SOM content, disturbance tends to promote losses of SOM. Dick and Gregorich (2004) cite tillage and erosion as the two greatest disturbance events that affect SOM in agricultural soils. Tillage effects on SOM and management strategies are discussed in detail below.

A tilled soil is susceptible to wind and water erosion (Franzluebbers, 2004). Erosive processes selectively remove SOM as it strips away a soil's A horizon (Janzen et al., 1998; Dick and Gregorich, 2004). The SOM loss problems associated with erosion are further compounded when a thinned A horizon is tilled, mixing the surface soil with subsoil (containing very little SOM) and diluting what SOM is present. As SOM is

depleted by disturbance a cycle of decline can take hold. With declining SOM, soil and crop productivity can decline, resulting in a reduction in primary production and thus fewer organic inputs into the soil thattranslates to further reductions in SOM (Gregorich et al., 1998).

There is agreement among scientists who have studied SOM that taking land out of native vegetation and converting it to agriculture almost invariably causes a decline in SOM (Magdoff, 1996; Janzen et al., 1997; Lal, 1998a; Weil and Magdoff, 2004; Magdoff and Weil, 2004; Lal et al., 2004; others). Janzen et al. (1997) state that this occurs because the land clearing and tillage associated with conversion to agriculture prompts a decrease in primary productivity and an increase of mineralization rates, thus altering the equilibrium state of SOM in that soil. After the native equilibrium state is disturbed a soil converted to agriculture will lose SOM over time until a new equilibrium is reached (Dick and Gregorich, 2004). Dick and Gregorich (2004) specifically list four factors that result in SOM loss when undisturbed lands are converted to agriculture:

One: There is less plant residue returned to soils in agroecosystems, partially due to the fact that some of the plant material is removed from the system at harvest.

Two: The plants native to the undisturbed ecosystem have been replaced with agricultural crops that may not have the same root and shoot biomass as the native vegetation.

Three: Conversion to agriculture, particularly through tillage, changes the microclimate at the soil surface and physically releases physically protected SOM, causing an increase mineralization rates.

Four: Wind, water, and tillage erosion processes causes preferential loss of finer materials associated with active pool SOM.

Soil tillage, physical disturbance of the soil

Soil tillage has been associated with seed bed preparation and weed control since the dawn of agriculture. Indeed, furrowed fields in the spring, bearing freshly turned earth is probably one of the most common mental images people associate with farming. In the last half century, however, evidence has mounted that tillage is a primary cause of SOM loss and soil degradation (Melsted, 1954; Bauer and Black, 1981, Magdoff, 1996; Janzen et al., 1997; Lal, 1998a; Weil and Magdoff, 2004; Magdoff and Weil, 2004; Lal et al., 2004; others). Long-term use of conventional tillage can cause a reduction in soil organic matter content (Van Doren et al., 1976; Cambardella and Elliot, 1993b). Cultivation of soils, especially by conventional tillage, causes disintegration of soil macroaggregates and exposes the particulate organic matter formerly sequestered within aggregates to microbial degradation (Cambardella and Elliot, 1992; Cambardella and Elliot, 1993b). A portion of this sequestered particulate organic matter is associated with the active pool of soil organic carbon (Parton et al., 1987; Paustian et al., 1992; Gregorich et al., 1994). The exposure of this particulate organic matter, along with the soil aeration and temperature increase that are also products of tillage, accelerates microbial activity and as a result microbial oxidation of soil organic C increases (Dalal and Henry, 1988; Paustian et al., 1997a). This oxidized C is lost to the atmosphere, respired as CO_2, and as a result SOM is degraded (Dalal and Henry, 1988; Paustian et al., 1997a).

Conservation tillage practices have been developed in part to control the loss of soil (and SOM) to erosion. A major objective of conservation tillage practices is to leave crop residues on the soil surface as opposed to incorporating them, thus covering the soil to a greater degree and slowing erosive processes (Franzluebbers, 2004). However these residues also undergo decomposition and while much of the C content of residues is respired as CO_2, some of it becomes SOM. Of the conservation tillage techniques in use the method that minimizes soil disturbance is no-tillage (Dick and Gregorich, 2004). Dick and Gregorich (2004) state that this method shows the most promise in preventing SOM loss and reversing losses incurred through prior tillage. No-tillage influences soil water storage thatin turn has an affect on crop production and microbial activity. In Minimizing physical disturbance of soil helps maintain the stability of macroaggregates and promotes the physical protection of SOM. Because mineralization takes place slower in no-till soils and more SOM is protected, root derived C is retained more effecively (Gale and Cambardella, 2000). This root derived C is increasingly becoming recognized as a major source of the positive SOC building effects of grasses and some high residue cover crops (Kuo et al., 1997; Römkens et al. 1999; Gale and Cambardella, 2000; Puget and Drinkwater, 2001). Plant residue return to the soil surface is maximized in no-till systems while at the same time minimizing soil-residue contact since the detritus is not incorporated. Minimizing plant residue contact with soil slows decomposition because moisture levels, nitrogen availability, and temperature ranges suitable for decomposition, as well as decomposers themselves, are more prevalent within the soil rather than on the soil surface (Wilson and Hargrove, 1986). Most of the impacts of no-till farming are seen in the shallowest sampling depths, near the rooting zone and crop residue inputs

(Dick, 1983; Blevins et al., 1985; Dick et al., 1991; Potter et al. 1998). Dick et al. (1991) found that continuous application of no-tillage to soils in Ohio caused an accumulation of SOM, nutrients and soil enzymes in the 0-20cm layer while also reducing surface water runoff. Blevins et al. (1985) found similar results on soils in Kentucky.

The disturbance of soil through tillage has effects upon indicators of active pool SOM that have been described in several studies. In studies comparing no-till soils to conventionally tilled soils, reductions in POM were seen in the conventionally tilled soils (Hussain et al., 1999; Guggenberger et al., 1999; Needelman et al., 1999). In similar studies comparing no-till and conventional tillage regimes, reductions were seen in microbial biomass C in conventionally tilled soils (Franzleubbers and Arshad, 1996; Salinas-Garcia et al., 1997). Six et al. (2000) saw variations in aggregate stability due to level of soil disturbance. Aggregate stability decreased with increased disturbance as follows: undisturbed soils under native vegetation > no-tilled soils > conventionally tilled soils (Six et al., 2000). Wander and Bollero (1999) found similar aggregate stability results in soils under similar conditions in Illinois. Likewise, Islam and Weil (2000) saw similar trends in their study on soil quality indicators in mid-Atlantic soils. Mineralizable C and mineralizable N have also been shown to be responsive to tillage. Several studies have shown higher levels of mineralizable C (Karlen et al., 1994a; Salinas-Garcia et al., 1997; Alvarez et al., 1998a; Wander and Bollero, 1999) and minealizable N (Doran, 1987; Salinas-Garcia et al., 1997; Needelman et al., 1999; Wander and Bollero, 1999) in no-tilled soils when compared to conventionally tilled soils.

Improved soil organic matter management methods

Soil organic matter levels in agriculture can be maintained or improved through minimizing disturbance events and carefully managing inputs. Using no-till practices have been shown to maintain and/or enhance SOM levels in the surface layer of soil. In addition to minimizing disturbance through no-till or reduced tillage practices, managing inputs in order to increase the amount of SOC becoming part of the soil ecosystem are also an important facet of sustainable agricultural systems (Dick and Gregorich, 2004; Franzluebbers, 2004; Magdoff and Weil, 2004). It has been shown that there is usually a direct relationship through time between the amount of organic inputs added to a soil and its SOM content (Paustian et al., 1997a; Studdert and Echeverría, 2000).

Input management can involve implementing more complex crop rotations (as opposed to monoculture) that include high residue crops (Magdoff and Weil, 2004). Grasses, legumes, or grass-legume mixes, as part of a crop rotation plan, provide large quantities of aboveground residues as well as dense root systems and have a positive impact on SOM content. In addition, in some crop rotation systems more crop residues can be produced due to higher yields seen in these rotation systems (Karlen et al., 1994b). Including pastures in a rotation has also been shown to improve SOM levels (Studdert et al., 1997). Another way to increase the amount of crop residues on a field is to annually grow more crops. One way to do this is with the use of cover crops. This strategy is discussed more specifically in the next section.

Dick and Gregorich (2004) state that a very efficient method used to build SOM is soil application of manures, processed biosolids, or composts. They state that because these substances have already undergone some decomposition (digestion in the case of manures, digestion and treatment in the case of biosolids, and composting) before being

applied to soils, some of the organic C contained in these substances has already been converted to recalcitrant forms. This allows for more C being sequestered in the soil as opposed to being respired into the atmosphere as CO_2. It should be noted, however, that with composts much of the labile C that would contribute to active pool SOM has been removed from these substances by the composting process. This outcome was demonstrated by Chromec and Magdoff (1984) who found that, when added to a soil, a composted mixture of biosolids and sawdust did not contribute as much organic C (or organic N, or CEC) as a noncomposted mixture of the same materials.

Allowing succession to take place so that agricultural lands revert to their native forest or grassland vegetation is also a way that SOM levels can be rebuilt in soils. The SOM buildup in these circumstances generally takes a long period of time (Weil and Magdoff, 2004). Syers and Craswell (1995) estimated that SOM rebuilding under native vegetation could take up to 35 years to achieve the SOM levels that were seen in that soil prior to agriculture. Guggenberger and Zech (1999) found that even soils that had been put into pasture (see below), and subsequently allowed to return to secondary forest, can take 18 years to gain back pre-cultivation levels of SOC. Since this type of conversion also reduces a farmer's harvestable land, the Conservation Reserve Program has been developed in the U.S. to provide monetary compensation to farmers for their financial losses (Weil and Magdoff, 2004). Weil and Magdoff (2004) note that the SOM gains attained in soils that have been allowed to return to native vegetation can quickly be lost if they are cultivated again with conventional tillage. However, there is evidence that much of the accumulated SOM can be conserved if management of these soils is done with no-till practices (Weinhold and Tanaka, 2001; Dao et al. 2002). In any case,

evidence has indicated that reversion to native grasses or forest provides the best means for a soil to reach the full SOM potential allowed by natural capacity factors (Cambardella and Elliot, 1992; Wander and Bollero, 1999; Six et al., 2000).

Soils that have been put into sod, perennial grass or pasture also accumulate high amounts of SOM (Magdoff, 1992; Pulleman et al., 2000; Bowman and Anderson, 2002; Franzluebbers and Studemann, 2002). Grasses are extremely high residue crops that produce dense, extensive root systems as well as large amounts of aboveground biomass that turn over annually (Magdoff, 1992; Franzluebbers and Studemann, 2002). Pulleman et al. (2000) found that only three years under grass can significantly increase SOM and that SOM benefits under grass management became increasingly pronounced as time under grass increased. Christensen and Johnston (1997) found a 10% increase in SOM after 3 years in grass. In pasture situations, separate studies by Jordan et al. (1995) and Franzluebbers et al. (2000) found that properly managed grazing enhanced the SOM building capabilities of grass vegetation with grazed pastures having higher C and N contents than soils under native rangeland (Jordan et al.,1995) or native forest (Franzluebbers et al., 2000). Despite the findings of Pulleman et al. (2000), and Christensen and Johnston (1997), some soils that have been extensively cultivated for very long periods and subsequently put into grass, sod or pasture management can still take a very long time to regain pre-cultivation total SOM levels. Christensen and Johnston (1997), working on the Rothamsted soils in England, observed that even after 36 years of continuous grass, the total SOC content of previously cultivated soils was still well below that of soils that had been under grass for at least 300 years. Thus active pool

indications are important when observing the effects of grass, sod, or pasture management.

The root biomass in these grass systems turns over yearly. There is a significant body of evidence showing that this root biomass may be the most important SOM contributor in these systems and that root biomass contributes to active pool SOM. Römkens et al. (1999) showed that most of the LF generated in soils converted from corn production to pasture was generated by root-derived SOM. In addition they found that 90% of the total SOC that had been lost during corn production was restored after 9 years of pasture. Further active pool influence of sod was seen by Cambardella and Elliot (1992) who found that in a soil under native sod 39% of total SOC was derived from POM associated C. In a seven year study by Weil et al. (1993) comparing 4 tillage regimes (no-till, two reduced-tillage systems, and conventional tillage) and including a 5th "treatment" of continuous grass, the grass system, at the conclusion of the study, had the highest total SOC, highest extractable C using three common extraction methods (K_2SO_4, H_2SO_4, and $NaHCO_3$), and the highest C by the active pool associated hot water extraction method. (Also of note in this study is that the no-till system had the second highest SOC levels in all of the categories of SOC tested, thus giving further evidence of the SOM maintaining and enhancing capabilities of no-till practices.) A study by Haynes (1999) involved long term pasture, continuous grass/clover, continuous grass, annual no-till grass, annual conventional-till grass, and long term arable soils. In this study microbial biomass C and microbial biomass N content followed the order: long term pasture > continuous grass/clover and continuous grass (which had comparable levels) > annual no-till grass > annual conventional-till grass > long term arable soils. Readily

mineralizable C and mineralizable N followed a similar trend, the exception being that: continuous grass/clover ≈ continuous grass ≈ annual no-till grass. The highest aggregate stability measurements in Haynes's (1999) study were also in the long-term pasture fields, followed closely by continuous grass/clover and continuous grass.

It is important to note that while building SOM for soil quality is a major function of organic input management, other considerations go into these management schemes. Supplying crops with nutrients is a major consideration for farmers when applying inputs. Potential pollution caused by excesses of these nutrients, particularly N leaching and runoff associated P, has to be considered when managing inputs (Magdoff and Weil, 2004). In addition, input management and SOM building is important to those working to mitigate global warming because soils with the capacity to hold more SOC than their present level can potentially be used as a sink for atmospheric CO_2 (Paustian et al., 1997b).

Increasing cropping intensity to build soil organic matter: The use of cover crops

One important concept in SOM management is that of cropping intensity. Intensive cropping systems annually grow multiple crops and more plant biomass in the same field. When combined with no-till practices, these intensive systems produce the largest increases in SOC seen under arable conditions (Wood et al., 1991; Franzluebbers et al., 1995; Ortega et al., 2002). Increasing the cropping intensity increases net primary production, leaving more residues on a soil, while no-tillage practices decrease the rate of mineralization.

There has been some evidence linking crop yields with SOM management through increased cropping intensity. Monreal et al. (1997) used CENTURY model simulations on data from long-term wheat production research plots. Their simulations indicated that soils under wheat-fallow cropping (lower cropping intensity) on average yielded less wheat (910 kg ha^{-1} yr^{-1}) than higher cropping intensity plots that were in either continuous wheat or cereal-hay rotations (1290 kg ha^{-1} yr^{-1}). They attributed the yield difference to SOM losses as a result of erosion in the wheat-fallow systems. The simulations by Monreal et al. (1997) also predicted increases in wheat yields in cereal-hay rotation plots with aggradations of SOM over the long-term. Their simulations predicted increases of 200 kg ha^{-1} and 840 kg ha^{-1} after 24 and 46 years of improving SOM contents, respectively. Work by Bowman et al. (1999) seems to support the SOM aspects of the computer simulations done by Monreal et al. (1997). Bowman et al. (1999) found that fallow periods were deleterious to SOM while continuous cropping had a positive effect on SOM, however SOM changes did not correlate with crop yields in their study.

One management practice that can be used to increase cropping intensity is the planting of winter cover crops. As the name implies, winter cover crops are generally grown when seasonal limitations prohibit production of commercial crops. High biomass winter cover crops, such as winter rye (*Secale cereal* L.) and annual ryegrass (*Lolium multiflorum* Lam.) provide substantial C inputs to soil because of the above- and belowground residues they produce. Kuo et al., (1997) indicated that winter rye is a good winter cover crop for building soil organic C because of the high levels of plant biomass deposited within and on top of the soil. They estimated rye dry biomass at the time of

killing to be 4.4 Mg/ha aboveground and 5 Mg/ha belowground to a depth of 20cm. Over 6 years Kuo et al., (1997) saw a small, but detectable, increase (0.5-1.0 g kg^{-1}) in total SOC on plots treated with winter rye. In a six-year study, Wagger et al. (1998) also observed increased total SOC associated with winter rye cover crops in the temperate humid region of Washington. Sainju et al. (2000) found that in a three-year study in conventionally tilled soils in the southern U.S. that have high C mineralization rates, rye cover crops maintained total SOC levels in soils.

Over the short-term, carbon inputs as a result of cover crops may not result in detectable gains in total SOC (Allison, 1973). Cover crop effects have been seen, however, in active pool SOM indicators. Mendes et al. (1999) saw increases in microbial biomass C, mineralizable C, mineralizable N, as well as levels of β-glucosidase, an enzyme indicative of soil microbe activity. Sainju et al. (2000) also saw increases in mineralizable C with the use of rye, hairy vetch, and crimson clover cover crops, with rye having the highest increases. Ndiaye et al., (2000) also saw a significant effect on microbial biomass C and soil β-glucosidase activity. Hu et al. (1997) saw two- to threefold increases in microbial biomass C, POM, and soil carbohydrates in cover crop treated plots as opposed to those left in winter fallow. Hermawan and Bomke (1997) found improved aggregate stability in plots treated with annual ryegrass, winter rye, and barley when compared to plots that were left bare. They found that improved aggregate stability with cover crops was related to increases in SOC. Puget and Drinkwater (2001) tracked ^{13}C labeled hairy vetch (*Vicia villosa* Roth.) roots and found that after one growing season nearly 50% of the root derived C (compared to 13% of shoot derived C)

was still present in the soil. They observed that much of the root derived C was associated with the POM fraction.

The use of cover crops to enhance soil productivity is not a new concept. Odland and Knoblauch (1938) conducted a study from 1900-1933 and found that compared to non-cover crop treated fields both rye and leguminous cover crop treated fields showed increased yields in both corn stover and grain over the duration of the study. Most of the literature dealing with yield effects in crops grown after winter cover crops deals with N cycling dynamics (Odland and KNoblauch, 1938; Smith et al., 1987; Blevins et al., 1990; Utomo et al., 1990; Torbert et al., 1996; Vaughan and Evanylo, 1998; Sainju et al., 2000; N'Dayegamiye and Tran, 2001; Sainju et al., 2001) as opposed to C related effects. In general, these papers deal with the use of leguminous cover crops such as hairy vetch that improve soil available N levels as cover crop residue decomposes, thus maintaining crop yields while reducing the need for N fertilizers. As discussed below, the direct quantification of SOM effects on crop yields has been difficult to measure. The little information available on yield effects seen after rye use is inconclusive. Odland and Knoblauch (1938) saw a significant increase in corn grain and stover following rye cover crops over a 34 year experiment and while they didn't directly attribute the increase to SOM or SOC they did cite increased water holding capacity, a soil property associated with SOM content, in rye treated fields. Kabir and Koide (2002) saw significantly higher yields of sweet corn on winter rye treated plots when compared to winter fallow plots. However rather than being due to increases in total SOC, they attributed the yield increases to enhanced P uptake in corn as a result of vesicular arbuscular mycorrhizal (VAM) colonization of the rye treated plots. They concluded that VAM activity declined

in the fallow plots as a result of the absence of host plants. Bauer and Busscher (1996) found significantly higher (by 327.84 kg ha^{-1} on average) yields in no-till cotton lint yields in fields that were treated with rye as opposed to fallow. However, they did not attribute the yield increase to any rye influenced soil parameter. McCracken et al. (1989) found that rye did not have significant effects on corn yields relative to no cover crop. Eckert (1988) saw some reduction in corn and soybean yields in silt loam and silty clay soils in Ohio. This reduction was attributed to corn stand reduction through the combined presence of rye mulch and previous crop residue. Raimbault et al. (1991) found that the yield problems associated with rye mulch and crop residue could be resolved by moving residue out of planting rows with disc furrowers. Several studies have noted reductions in corn yields after rye and attributed the reduction to possible allelopathic effects of rye (Raimbault et al., 1990; Kessavalou and Walters, 1997).

In addition to C and N inputs, cover crops are used in agricultural systems for a multitude of reasons. They protect against erosion by intercepting raindrops, preventing detachment of soil particles. They also slow runoff as it travels over the soil surface (Karlen and Cambardella, 1996). Winter rye and Italian ryegrass (*Lolium perenne* L.) have been shown to be beneficial for use as catch crops in the fall, scavenging residual N and reducing groundwater and estuarine pollution via leaching (Brinsfield et al., 1988; Staver and Brinsfield, 1990). Magdoff and Weil (2004) briefly review and reference numerous studies on cover crops that are beneficial with regards to pest management and weed control.

Soil and crop productivity relationships with soil organic matter

Soil organic matter functions within a soil ecosystem are a key factor in soil productivity and, in agronomic systems, in the productivity of crops. Soil organic matter affects soil fertility as a source and a sink for plant nutrients (particularly N, P, S and micronutrients) in soils (Dick and Gregorich, 2004). In addition SOM has a high exchange capacity for macro- and miconutrient cations (Sikora and Stott, 1996). In some agricultural soils SOC may provide 40-50% of the soil's CEC thatsignificantly contributes to soil chelation and buffering capacities (Loveland and Webb, 2003). Through its influence on soil structure, SOM aids infiltration of water, water holding capacity, and circulation of air within a soil (Gregorich et al, 1994). Well-structured soils also tend to be more resistant to erosion keeping nutrient bearing topsoil in place as opposed to washed away as sediments. The biological diversity of high SOM soils helps to suppress crop diseases and pests, while the dark coloration of SOM enhances soil heat absorption speeding the warm-up of soil in spring and thus allows earlier plant germination (Sikora and Stott, 1996). Soil organic matter has also been associated with improved water use efficiency by plants through the stimulation of plant root development (Pieri, 1992).

The most common and practical way to measure crop productivity is through the measurement of crop yields. Loveland and Webb (2003) state that crop yields in the last half century have often increased in spite of the fact that, in general, SOM levels have decreased. However, a portion of these yield increases can most likely be attributed to industrialized farming practices that relied on mineral salts for plant nutrition and focused primarily on production rather than the long term sustainability of the agroecosystem. A study of soils in Germany by Beyer et al. (1999) suggested that SOM levels had little to

do with crop yields. In their study soils with lower SOC levels showed no decrease in crop yields when compared to soils with regionally "typical" SOC levels. The soils studied, however, were heavily fertilized receiving an annual average of 160 kg of mineral N ha^{-1} annually, with some plots receiving as much as 320 kg N ha^{-1}. While on the surface it may seem economically feasible to utilize mineral salt fertilizers to obviate SOM management, the underlying costs in fossil-fuel dependent fertilizer production and the environmental damage associated with excess fertilizer use (ie: leaching of nutrients and subsequent eutrophication of lakes and estuaries) forces one to question the long-term viability of this practice.

With agricultural researchers and producers increasingly devoting attention to sustainability, it has become even more important to gain a greater understanding of the relationship between SOM and crop yields. While SOM affects critical soil functions that in turn define a soil's productivity and thus the productivity of crops produced in that soil, demonstration of a direct SOM influence on crop yields can often be difficult to prove (Karlen et al., 1992; Seybold et al., 1996). Dick and Gregorich (2004) state that the capacity of a soil to hold SOM is affected by five capacity factors: climate, landscape, texture, inputs and disturbance. Of these factors, climate, landscape and texture are defined by nature, while inputs and disturbance are affected by soil management. The natural capacity factors vary widely across different soils. When comparing crop productivity throughout a range of soils, rather than being attributable to SOM levels, yield effects are often more attributable to these natural capacity factors or to an interaction between the factors and SOM (Weil and Magdoff, 2004).

Some scientists have demonstrated that SOM levels explain some of the variability in crop yields. Kravchenko and Bullock (2000) found that in Illinois agricultural fields, soil properties explained about 30% of corn yield variability with SOM having more influence than CEC, soil P content and soil K content. The SOM effect was greatest in the low SOM Alfisols included in their study (the other soils were of the Mollisol order) which seems to corroborate the idea that SOM content is most important in soils with inherently low SOM levels. In another study in Illinois, Majchrzak et al. (2001) found that when SOM level was the only variable considered there was a high positive correlation ($r^2 = 0.67$) with wheat yield. Alvarez et al. (2002) found that, in the humid Pampa of Argentina, SOC was the soil property most associated with wheat yield ($r^2 = 0.25$) with an average yield difference of 2200 kg ha^{-1} between high and low SOM soils. Alvarez et al. (2002) also found that several SOM active pool measures could partially explain yield variability. When LF and mineralizable N were included in a model with available mineral N and rainfall, the model accounted for 50% of the variability in wheat yield. Stine and Weil (2002) found that SOC was predictive of macroaggregate stability and soil porosity across different tillage systems in south central Honduras. In turn, macroaggregate stability, along with potassium permanganate oxidizable C, were highly correlated with crop productivity. They suggested that increased SOC, particularly active pool C, was related to improved soil structure, which positively affected productivity.

A few studies have related losses or gains in SOM levels directly to quantitative differences in crop yields. In the semiarid Pampas of Argentina Diaz-Zorita et al. (1999) found that soils with SOC content in the 0-20cm surface of lower than 42 Mg ha^{-1} show

marked decreases in crop productivity associated with losses in SOC. In their study a SOC loss of 1.0 Mg ha^{-1} was associated with a 40 kg ha^{-1} reduction in wheat grain yield. Bauer and Black (1994) reported that on a yearly basis the highest total aboveground dry matter and grain yields were associated with the highest SOM contents. The soil areas they studied had SOM contents ranging from 64 to 142 Mg ha^{-1}. When relating wheat yields to SOM content they found that every additional 1.0 Mg ha^{-1} of SOM was equivalent to an increase of 35.2 kg ha^{-1} of aboveground dry and 15.6 kg ha^{-1} of grain yield. They suggested that the main contribution of SOM to crop productivity was in the form of enhanced available N. Weil and Magdoff (2004) point out that in many SOM studies it is difficult to discern a causal relationship with crop yield because the SOM effects observed are often confounded with other effects of the imposed treatments used to alter SOM levels.

Treatments used by researchers to affect SOM can include crop rotations, tillage systems, or manure applications. Assessments of SOM effects in these circumstances can be obscured by other effects of the imposed treatments such as structural and hydrologic effects resulting from soil mixing by tillage or N inputs resulting from legume residues or manure applications. Strickling (1975), as cited by Weil and Magdoff (2004), isolated the effect of SOC by imposing, over 20 years, crop rotations that altered soil C content. In the final years of the experiment all plots were treated alike (including fertilizer application) and the residual effects of he aggradations or depletions of SOC were assessed. Strickling (1975) found that SOC levels accounted for 82-84% of the variation in corn yields regardless of N fertilization levels. He suggested that SOM influenced crop yields by enhancing water infiltration through improved aggregation.

Agricultural researchers, farmers and extension agents cite a need for soil quality assessment tools at the field level that can facilitate the making of soil management decisions (Liebig and Doran, 1999; Wander and Drinkwater, 2000). The role of SOM in soil quality has been widely discussed (Doran and Parkin, 1994; Gregorich et al, 1994; Karlen and Cambardella, 1996; Syers and Craswell, 1995; Seybold et al., 1996; Christensen and Johnston, 1997; Janzen et al., 1997; Lal, 1998; Haynes, 2000; Islam and Weil, 2000; Weil and Magdoff, 2004; and others) however the concept of using a SOM measurement to identify soils that are likely show gains in productivity with improved SOM management practices, such as cover crops is not well represented in current literature. Greer and Schoenau (1997) and Carter et al. (2004) discuss hierarchical frameworks that incorporate SOM into prediction of soil quality and the impacts of management practices on soil quality. These frameworks are quite complex, involving many other factors, and while they are conceptually beneficial to the research community, producers and extension agents may find them impractical for on farm use. Many papers suggest using SOM or active pool SOM components to assess or monitor management induced changes in soils (LeFroy et al., 1993; Biederbeck et al., 1994; Gregorich et al., 1994; Ellert and Bettany, 1995; Salinas-Garcia et al., 1997; Campbell et al., 1999; Bowman et al., 1999; Maddonni et al., 1999; Ndiaye et al., 2000 and others) however, while in some cases it may be implied, none of these directly propose using these tests to identify soils where improved management could lead to improved productivity. In part, this is likely due to the previously mentioned fact that total SOM does not respond rapidly to SOM management as well as the fact that SOM impacts on crop yields are difficult to quantify. In addition most methods used to estimate the active

pool involve time consuming incubations (mineralizable N, mineralizable C, microbial biomass, and microbial biomass C) or sieving processes (POM, light fraction SOM) and thus are not practical for rapid assessments. In a study on soil degradation, Bruce et al. (1995) observed that restoration and maintenance of soil productivity is associated with the maintenance of decomposing mulch on the soil surface. They also found that, in the 40 fields they studied, SOC in the A horizon was the manageable soil component that could significantly influence crop available water and reduce erosion. In addition to low SOC, they observed that degraded soils had low levels of water stable aggregates, low rainfall infiltration and low crop biomass production. Bruce et al. (1995) however do not directly propose any SOC testing guidelines aimed at identifying fields with SOM levels that could be improved. Tiessen et al. (1994) suggest that the quantification of SOM cycling might be an important guide when assessing agricultural potential of soils. There are several studies that attempt to quantify SOM with the goal of minimizing of losses (Bauer and Black, 1994; Bruce et al., 1995; Shang and Tiessen, 1997; Diaz-Zorita et al., 1999). Loveland and Webb (2003) found, in a review of current literature, that there is little quantitative evidence for a minimum level of SOM for soils, below which soil quality sharply declines. They did find evidence that there might be a SOC range across a broad assortment of soil types in which soils are most functional. According to Loveland and Webb (2003) this range needs to be researched further and quantitative evidence for it needs to be developed. Also noted by Loveland and Webb (2003) is the need for more research on active pool SOM components and how they influence soil properties in soils under different land uses.

An active pool SOM estimation that may be useful as a tool to guide land management decisions is labile C measured by $KMnO_4$ oxidation. Blair et al., (1995) suggested that labile C measured by $KMnO_4$ oxidation and total SOC can be used to calculate a carbon management index (CMI) to monitor management induced changes in soil quality. According to Blair et al. (1995) there is no ideal CMI value that suggests a soil is healthy, however the CMI can be used in conjunction with undisturbed "reference" soils to gauge whether a soil is in decline or is being rehabilitated. Weil et al. (2003) suggest that a $KMnO_4$ oxidizable C measurement method, modified for field use, can be used evaluate soil quality impacts of management practices. In order for a $KMnO_4$ oxidizable C test to be useful in determining if a soil's productivity can be enhanced through management practices, research needs to be conducted on how well such a test will predict both crop and soil quality indicator responses to management practices geared toward improving SOM content.

Conclusions

In the face of questions about the sustainability of modern agriculture, soil quality has become a primary focus of both farmers and researchers. The development of soil quality assessment tools is important both for the purpose of gaining a better understanding of the chemical, biological, and physical parameters that determine a soil's agricultural quality, and for the purpose of being able to demonstrate to producers that they can improve the quality of some soils through management. Likewise researchers need to continue to listen to farmers and gain understanding of how these farmers, who intimately work with nature, perceive soil quality issues and constraints (Wander and

Drinkwater, 2000). Researchers can then further study these parameters and provide management oriented feedback and tools that enhance farmers' abilities to make soil management decisions.

Soil organic matter is the key to sustainable soil quality management (Larson and Pierce, 1991; Doran and Parkin, 1994; Sikora and Stott, 1996; Weil and Magdoff, 2004). In the interest of maintaining or improving soil quality, many farmers are incorporating conservation management and SOM building practices into their farming regime. Many scientists involved in agriculture are working towards gaining a better understanding of SOM in terms of soil quality issues and indicators so that sustainability can be maximized.

Much of this review has focused on cropping and soil management practices that can be implemented to build SOM for soil quality purposes. While many farmers have incorporated conservation practices into their cropping systems, there are many more who could benefit from the adoption of these techniques. For example in 1996 conservation tillage practices were being used on about 42 Mha in the United States, which translates to about 36 percent of planted cropland (CTIC, 1998). Lal et al., (1998b) have estimated that approximately 60% of arable land in the United States could be farmed successfully with conservation tillage. The C sequestration potential of these lands is important for building SOM for soil quality and for mitigation of global warming (Paustian et al., 1997b; Lal et al., 1998b).

Development of soil quality evaluation tools from which scientists can gauge changes in soil quality and demonstrate these changes in a practical fashion to farmers is an important challenge to the agricultural and soil science community. Practical

demonstrations to farmers can be used to encourage them to adopt conservation practices if the practices are suitable for their situation. When these tools hinge on SOM or active pool SOM they should be able to show sensitivity to improved (or deleterious) soil management practices. Additionally, they should also have some practical importance to producers. One way that these tools can have practical implications is through the ability to predict soil and crop responses to improved SOM management. A simple soil quality test with the ability to predict crop yield improvement and soil functional improvement with the use of certain management practices would be a great asset when educating producers about conservation or SOM building management practices. While no single tool may constitute a "silver-bullet" for assessment of soil quality researchers and farmers must continue to work together to develop a "tool box" that can aid in the development of agroecosystems that are profitable, practical, environmentally sound, and sustainable.

Estimation of active pool labile C through $KMnO_4$ oxidation may be a useful addition to the soil management "tool box". The modified method developed by Weil et al. (2003) is suitable for rapid soil quality testing at the field level and might be used to evaluate whether a field's productivity could benefit from improved SOM management techniques. In order to be useful in this capacity such a test should be predictive of soil functional response and crop response to SOM management practices. Research needs to be conducted on how well the Weil et al. (2003) $KMnO_4$ test can predict crop responses and soil quality indicator responses to management practices that are geared toward improving SOM content. The use of winter rye cover crops would be a good management practice to test because of the high C input value of this cover crop. Unlike leguminous cover crops, rye would not confound crop yields through the input of N, thus

crop responses to C inputs could be evaluated. Paired fields of the same soil type but differing in soil quality due to past management history should be used for testing the impacts of a rye cover crop on crop responses and soil functional responses along with the predictive value of a soil quality test such as the $KMnO_4$ oxidizable C test. Assuming that a field that tests higher in labile C has better soil quality and assuming that the use of a winter rye cover crop increases the amount of labile C in a soil, a field that initially tests low in labile C should show more crop response and more response in soil quality indicators to soil management that includes a rye cover crop compared to a field that initially tests high in labile C.

REFERENCES

Allison, F.E. 1973. Soil organic matter and its role in crop production. Dev. Soil Sci. 3. Elsevier, Amsterdam.

Alvarez, R., M.E. Russo, P. Prystupa, J.D. Schneider, and L. Blotta. 1998a. Soil carbon pools under conventional and no-tillage systems in the Argentine Rolling Pampa. Agron. J. 90:138-143.

Alvarez, C.R., R. Alvarez, M.S. Grigera, and R.S. Lavado. 1998b. Associations between organic matter fractions and the active soil microbial biomass. Soil Biol. and Biochem. 30:767-773.

Alvarez, R., C.R. Alvarez, and H.S. Steinbach. 2002. Association between soil organic matter and wheat yield in humid Pampa of Argentina. Comm. Soil Sci. Plant Anal. 33:749-757.

Acton, D.F., and G.A. Padbury. 1993. A conceptual framework for soil quality assessment and monitoring. *In* D.F. Acton (Ed.) A Program to Assess and Monitor Soil Quality in Canada: Soil Quality Evaluation Program Summary. Research Branch, Agriculture and Agri-Food Canada: Ottawa, Ontario.

Angers, D.A., and G.R. Mehuys 1989. Effects of cropping on carbohydrate content and water stable aggregation of a clay soil. Can. J. Soil Sci. 69:373-380.

Arshad, M.A., and G.M. Coen. 1992. Characterization of soil quality: Physical and chemical criteria. Am. J. Altern. Agric. 7:25-31.

Banerjee, M.R., and S.J. Chapman. 1996. The significance of microbial biomass sulphur in soil. Biol. Fertil. Soils 22:116-125.

Bauer, A., and A.L. Black. 1981. Soil carbon, nitrogen, and bulk density comparisons in two cropland tillage systems after 25 years and in virgin grassland. Soil Sci. Soc. Am. J. 45:1166-1170.

Bauer, A., and A.L. Black. 1994. Quantification of the effect of soil organic matter content on soil productivity. Soil Sci. Soc. Am. J. 58:185-193.

Bauer, P.J., and W.J. Busscher, 1996. Winter cover and tillage influences on Coastal Plain cotton production. J. Product. Agric. 9:50-54.

Bell, M.J., P.W. Moody, R.D. Connolly, and B.J. Bridge. 1998. The role of active fractions of soil organic matter in physical and chemical fertility of Ferrosols. Aust. J. Soil Res. 36:809-819.

Bell, M.J., P.W. Moody, S.A. Yo, and R.D. Connoly. 1999. Using active fractions of soil organic matter as indicators of the sustainability of Ferrosol farming systems. Aust. J. Soil Res. 37:279-287.

Beyer, L, K. Sieling, and K. Pingpank. 1999. The impact of a low humus level in arable soils on microbial properties, soil organic matter quality and crop yield. Biol. Fertil. Soils 28:156-161.

Bezdicek, D.F., R.I. Papendick, and R. Lal. 1996. Importance of soil quality to health and sustainable land management. p. 1-8. *In* J.W.Doran and A.J. Jones (ed.) Methods for assessing soil quality. SSSA Spec. Publ. 35. SSSA, Madison, WI.

Biederbeck, V.O., H.H. Janzen, C.A. Campbell, R.P. Zentner. 1994. Labile soil organic matter as influenced by cropping practices in an arid environment. Soil Biol. Biochem. 26:1647-1656

Blair, G.J., R.D.B. Lefroy, and L. Lisle. 1995. Soil carbon fractions based on their degree of oxidation and the development of a carbon management index for agricultural systems. Aust. J. Agric. Res. 46:1459-1466.

Blair, G.J., R. Lefroy, A. Whitbread, N. Blair, and A. Conteh. 2001. The development of the $KMnO_4$ to determine labile carbon in soil and its use in a carbon management index. p. 323-337. *In* R. Lal, J.M. Kimble, R.F. Follett, and B.A. Stewart (ed.) Assessment methods for soil carbon. Lewis Publishers, Boca Raton, FL.

Blair, N., and G.J. Crocker. 2000. Crop rotation effects on soil carbon and physical fertility of two Australian soils. Aust. J. Soil Res. 38:71-84.

Blevins, R.L., W.W. Frye, and M.S. Smith. 1985. The effects of conservation tillage on soil properties. p. 99-110. In F.M. D'Itri (ed.) A systems approach to conservation tillage. Lewis Publishers, Chelsea, MI.

Blevins, R.L., J.H. Herbeck, and W.W. Frye. 1990. Legume cover crops as a nitrogen source for no-till corn and grain sorghum. Agron. J. 82:769-772.

Bowman, R.A., M.F. Vigil, D.C. Nielsen, and R.L. Anderson. 1999. Soil organic matter changes in intensively cropped dryland systems. Soil Sci. Soc. Am. J. 63:186-191.

Bowman, R.A., and R.L. Anderson. 2002. Conservation Reserve Program: effects on soil organic carbon and preservation when converting back to cropland in northeastern Colorado. J. Soil Water Conserv. 57:121-126.

Bradford, M.A., T.H. Jones, R.D. Bardgett, H.I.J. Black, B. Boag, M. Bonkowski, R. Cook, T. Eggers, A.C. Gange, S.J. Grayson, E. Kandeler, A.E. McCaig, J.E. Newington, J.I. Prosser, H. Setala, P.L. Staddon, G.M. Tordoff, D. Tscherko, and J.H. Lawton. 2002. Impacts of soil faunal community composition on model grassland ecosystems. Science 298:615-618.

Brady, N.C., and R.R. Weil. 2002. The Nature and Properties of Soils. Thirteenth edition. Prentice Hall. Upper Saddle River, New Jersey.

Brinsfield, R., K. Staver, and W. Magette. 1988. The role of cover crops in reducing nitrate leaching to groundwater. p. 127-146. *In* Agricultural impacts on groundwater. National Well Water Assoc., Dublin, OH.

Bruce, R.R., G.W. Langdale, L.T. West, and W.P. Miller. 1995. Surface soil degradation and soil productivity restoration and maintenance. Soil Sci. Soc. of Am. J. 59:654-660.

Buyanovsky, G.A., M. Aslam and G.H. Wagner. 1994. Carbon turnover in soil physical fractions. Soil Sci. Soc. Am. J. 58:1167-1173.

Cambardella, C.A., and E.T. Elliot, 1992. Particulate soil organic matter changes across a grassland cultivation sequence. Soil Sci. Soc. Am. J. 56:777-783.

Cambardella, C.A., and E.T. Elliot, 1993a. Methods for physical separation and characterization of soil organic matter fractions**.** Geoderma 56:449-457.

Cambardella, C.A., and E.T. Elliot, 1993b. Carbon and nitrogen distribution in aggregates from cultivated and native grassland soils. Soil Sci. Soc. Am. J. 57:1071-1076.

Campbell, C.A., V.O. Biederbeck, .G. McConkey, D. Curtin, and R. P. Zentner. 1999. Soil quality – Effects of tillage and fallow frequency. Soil organic matter quality as influenced by tillage and fallow frequency in a silt lom in southwester Saskatchewan. Soil Biol. Biochem. 31:1-7.

Carter, M.R, S.S. Andrews, and L.E. Drinkwater. 2004. Systems approaches for improving soil quality. p. 261-281. *In* P. Schjonning, S. Elmholt, and B.T. Christensen (ed.) Managing Soil Quality: Challenges in modern agiculture. CABI Publishing, Oxon, United Kingdom.

Chenu, C. 1995. Extracellular polysaccharides: An interface between microorganisms and soil constituents. p. 217. *In* P.M. Huang, J. Berthelin, J.-M. Bollag, W.B. McGill (Ed.) Environmental impact of soil component interactions: Land quality, natural and anthropogenic organics, Vol. 1. CRC Press, Boca Raton, FL.

Cheshire, M.V., A. Lomax, and C.M. Mundie. 1989. Structure of soil carbohydrates resistant to periodate oxidation. J. Soil. Sci. 40:865-872.

Christensen, B.T. 1992. Physical fractionation of soil and organic matter in primary particle size and density separates. p. 1-90. *In* Advances in soil science, Vol. 20. Springer-Verlag, New York.

Christensen, B.T. and A.E. Johnston. 1997. Soil organic matter and soil quality: Lessons learned from long-term experiments at Askov and Rothamsted. p. 399-430. *In* E.G. Gregorich and M.R. Carter (ed.) Soil quality for crop production and ecosystem health. Elsevier Science Publishers B.V., Amsterdam, The Netherlands.

Chromec, F.W. and F.R. Magdoff. 1984. Alternative methods fore using organic materials: composting vs. adding directly to soil. J. Environ. Sci. Hlth. 19:697-711.

Cotton, F.A., and G. Wilkinson. 1965. Advanced inorganic chemistry. 4th ed. Interscience Publishers, John Wiley and Sons, New York. p. 839-840.

CTIC. 1998. 17th Annual Crop Residue Management Survey Report. Conservation Technology Information Center, West Lafayette, IN, USA.

Dalal, R.C., and R.J. Henry. 1988. Cultivation effects on carbohydrate contents of soil and soil fractions. Soil Sci. Soc. Am. J. 52:1361-1365.

Dao, T.H., J.H. Stiegler, J.C. Banks, L.B. Boerngen, and B. Adams. 2002. Post-contract land use effects on soil carbon and nitrogen in conservation reserve grassland. Agron J. 94:146-152.

Davidson E.A., L.F. Galloway, and M.K. Strand. 1987. Assessing soil available carbon: Comparison of techniques across selected forest soils. Comm. Soil Sci. Plant Anal. 18:45-64.

DeLuca, T.H., and D.R. Keeney. 1994. Soluble carbon and nitrogen pools of prairie and cultivated soils: Seasonal variation. Soil Sci. Soc. Am. J. 58:835-840.

Díaz-Zorita, M., D.E. Buschiazzo, and N. Peinemann. 1999. Soil organic matter and wheat productivity in the semiarid Argentine Pampas. Agron. J. 91:276-279.

Dick, W.A. 1983. Organic carbon, nitrogen, and phosphorus concentrations and pH in soil profiles as affected by tillage intensity. Soil Sci Soc, Am. J. 47:102-107.

Dick, W.A., E.L. McCoy, W.M. Edwards, and R. Lal. 1991. Continuous application of no-tillage to Ohio soils. Agron J. 83:65-73.

Dick, W.A., and E.G. Gregorich. 2004. Developing and maintaining soil organic matter levels. p. 103-120. *In* P. Schjonning, S. Elmholt, and B.T. Christensen (ed.) Managing Soil Quality: Challenges in modern agiculture. CABI Publishing, Oxon, United Kingdom.

Doran, J.W. 1987. Microbial biomass and mineralizable nitrogen distributions in no-till and plowed soils. Biol. Fertil. Soils 5:68-75.

Doran, J.W., and T.B. Parkin. 1994. Defining and assessing soil quality. p. 3-21. *In* J.W.Doran, D.C. Coleman, D.F. Bezdicek, and B.A. Stewart (ed.) Defining soil quality for a sustainable environment. SSSA Spec. Publ. 35. SSSA, Madison, WI.

Doran J.W., and M.R. Zeiss. 2000. Soil health and sustainability: Managing the biotic component of soil quality. Appl. Soil Ecol. 15:3-11.

Doran J.W. 2002. Soil health and global sustainability: Translating science into practice. Agric. Ecosyst. Environ. 88:119-127.

Dormaar, J.R. 1983. Chemical properties of soil and water-stable aggregates after sixty yeas of cropping to spring wheat. Plant Soil 75:51-61.

Duxbury, J.M., M.S. Smith, and J.W. Doran. 1989. Soil organic matter as a source and sink of plant nutrients. p. 33-67. *In* D.C. Coleman, J.M. Oades, and G. Uehara (ed.) Dynamics of soil organic matter in tropical ecosystems. NifTAL Project, Dept. of Agronomy and Soil Science, College of Tropical Agriculture and Human Resources, University of Hawaii, Honolulu, HI.

Eckert, D.J. 1988. Rye cover crops for no-tillage corn and soybean production. J. Prod. Agric. 1:207-210.

Ellert, B.H. and J.R. Bettany. 1990. Calculation of organic matter and nutrients stored in soils under contrasting management regimes. Can. J. Soil Sci. 75:529-538.

Elliot, E.T., 1986. Aggregate structure and carbon, nirtrogen, and phosphorus in native and cultivated soils. Soil Sci. Soc. Am. J. 50:627-633.

Franzluebbers, A.J., F.M. Hons, and V.A. Saladino. 1995. Sorghum, wheat, and soybean production as affected by long-term tillage, crop sequence, and N fertilization. Plant Soil 173:55-65.

Franzluebbers, A.J., and M.A. Arshad. 1996. Soil organic matter pools during early adoption of conservation tillage in Northwestern Canada. Soil Sci. Soc. Am. J. 60:1422-1427.

Franzluebbers, A. J., J.A. Stuedemann, H.H. Schomberg,and S.R. Wilkinson. 2000. Soil organic C and N pools under long-term pasture management in the Southern Piedmont USA. Soil Biol. Biochem. 32:469-478.

Franzluebbers, A. J., and J.A. Stuedemann. 2002. Particulate and non-particulate fractions of soil organic carbon under pastures in the Southern Piedmont USA. Environ. Pollution 116(Suppl. 1):S53-S62.

Franzluebbers, A.J. 2004. Tillage and residue management effects on soil organic matter. p. 227-268. *In* F. Magdoff and R.R. Weil (ed.) Soil organic matter in sustainable agriculture. CRC Press. Boca Raton, FL.

Gale, W.J. and C.A. Cambardella. 2000. Carbon dynamics of surface residue- and root-derived organic matter under simulated no-till. Soil Sci. Soc. Am. J. 64:190-195.

Greer, K.J. and J.J. Schoenau. 1997. Toward a framework for soil quality assessment and prediction. p. 313-321. *In* E.G. Gregorich and M.R. Carter (ed.) Soil quality for crop production and ecosystem health. Elsevier Science Publishers B.V., Amsterdam, The Netherlands.

Gregorich, E.G., M.R. Carter, D.A. Angers, C.M. Monreal, and B.H. Ellert. 1994. Towards a minimum data set to assess soil organic matter quality in agricultural soils. Can. J. Soil Sci. 74:367-385.

Gregorich, E.G., K.J. Greer, D.W. Anderson, and B.C. Liang. 1998. Carbon distribution and losses: Erosion and deposition effects. Soil Tillage Res. 47:291-302.

Guggenberger, G., S.D. Frey, J. Six, K. Paustian, and E.T. Elliot. 1999. Bacterial and fungal cell-wall residues in conventional and no-tillage agroecosystems. Soil Sci. Soc. Am. J. 63:1188-1198.

Guggenberger, G., and W. Zech. 1999. Soil organic matter composition under primary forest, pasture, and secondary forest succession, Region Huetar Norte, Costa Rica. For. Ecol. Manage. 124:93-104.

Gunapala, N., and K.M. Scow. 1998. Dynamics of soil microbial biomass and activity in conventional and organic farming systems. Soil Biol. Biochem. 30:805-816.

Gupta V.V.S.R., and J.J. Germida. 1988. Distribution of microbial biomass and its activity in different soil aggregate size classes as affected by cultivation. Soil Biol. Biochem. 20:777-786.

Haynes, R.J. 1999. Labile organic matter fractions and aggregate staability under short term, grass based leys. Soil Biol. Biochem. 31:1821-1830.

Haynes, R.J. 2000. Labile organic matter as an indicator of organic matter quality in arable and pastoral soils in New Zealand. Soil Biol. Biochem. 32:211-219.

Heil, D., and G Sposito. 1997. Chemcal attributes and processes affecting soil quality. p. 59-70. *In* E.G. Gregorich and M.R. Carter (ed.) Soil quality for crop production and ecosystem health. Elsevier Science Publishers B.V., Amsterdam, The Netherlands.

Hermawan, B., and A.A. Bomke. 1997. Effects of winter cover crops and successive spring tillage on soil aggregation. Soil Tillage Res. 44:109-120.

Herrick, J.E.. 2000. Soil quality: An indicator of sustainable land management? Appl. Soil Ecol. 15:75-83.

Houghton, R.A., J.E. Hobbie, J.E. Melillo, B. Moore, B.J. Peterson, G.R. Shaver, and G.M. Woodwell. 1983. Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: A new release of CO_2 to the atmosphere. Ecol. Monogr. 53:235-262.

Hsieh, Y.-P. 1992. Pool size and mean age of stable organic carbon in cropland. Soil Sci. Soc. Am. J. 56:460-464.

Hussain, I., K.R. Olson, and S.A. Ebelhar. 1999. Long-term tillage effects on soil chemical properties and organic matter fractions. Soil Sci. Soc. Am. J. 63:1335-1341.

Hu, S., N.J. Grunwald, A.H.C. van Bruggen, G.R. Gamble, L.E. Drinkwater, C Shennan, and M.W. Demment. 1997. Short-term effects of cover crop incorporation on soil carbon pools and nitrgen availability. Soil Sci. Soc. Am. J. 61:901-911.

Islam, K.R., and R.R. Weil. 1998. Microwave irradiation of soil for routine measurement of microbial biomass carbon. Biol.Fertil. Soils. 27:408-416.

Islam, K.R. and R.R. Weil. 2000. Soil quality indicator properties in mid-Atlantic soils as influenced by conservation management. J. Soil Water Conserv. 55:69-78.

Janzen, H.H., C.A. Campbell, B.H. Ellert, and E. Brremer. 1997. Soil organic matter dynamics and their relationship to soil quality. p. 277-291. *In* E.G. Gregorich and M.R. Carter (ed.) Soil quality for crop production and ecosystem health. Elsevier Science Publishers B.V., Amsterdam, The Netherlands.

Janzen, H.H. C.A. Campbell, E.G. Gregorich, and B.H. Ellert. 1998. Soil carbon dynamics in Canadian agroecosystems. p. 57-80. In R. Lal, J. Kimble, R.F. Follet, and B.A. Stewart (ed.) Soil processes and the carbon cycle. CRC Press, Boca Raton, FL.

Jenkinson, D.S. and D.S. Powlson. 1976. The effects of treatments on metabolism in soil. V. A method formeasuring soil biomass. Soil Biol. Biochem. 8:209-213.

Jenkinson, D.S., and J.H. Rayner. 1977. The turnover of soil organic matter in some of the Rothamsted classical experiments. Soil Sci. 123:298-305.

Jenkinson, D.S., and J.N. Ladd. 1981. Microbial biomass in soil: Measurement and turnover. p. 415-471. *In* E.A. Paul and J.N. Ladd (ed.) Soil Biochemistry. Vol. 5. Marcel Dekker, New York.

Jenkinson, D.S. 1988. Determination of microbial biomass carbon and nitrogen in soil. p. 368-386. *In* J.R. Wilson (ed.) Advances in nitrogen cycling in agricultural ecosystems. CABI Publishing, Oxon, England

Jordan, D., R.J. Kremer, W.A. Bergfield, K.Y. Kim, and V.N. Cacino. 1995. Rangeland soil carbon and nitrogen responses to grazing. J. Soil Water Conserv. 50:294-298.

Kabir, Z. and R.T. Koide. 2002. Effect of autumn and winter mycorerhizal cover crops on soil properties, nutrient uptake and yield of sweet corn in Pensylvania, USA. Plant Soil 238:205-215.

Karlen, D.L., N.S. Eash, and P.W.Unger. 1992. Soil and crop management effects on soil quality indicators. Am J. Altern. Agric. 7:48-55.

Karlen, D.L., N.C. Wollenhaupt, D.C. Erbach, E.C. Berry, J.B. Swan, N.S. Eash, and J.L. Jordahl. 1994a. Long-term tillage effects on soil quality. Soil Tillage Res. 32:313-327.

Karlen, D.L., G.E. Varvel, D.G. Bullock, and R.M. Cruse. 1994b. Crop rotations for the 21st century. Adv. Agron. 53:1-45.

Karlen, D.L., and C.A. Cambardella. 1996. Conservation strategies for improving soil quality and organic matter storage. p. 395-420. *In* M.R. Carter, and B.A. Stewart (ed.) Structure and organic matter storage in agricultural soils. CRC Press, Boca Raton, FL.

Karlen, D.L., S.S. Anderws, and J.W. Doran. 2001. Soil quality: Current Concepts and Applications. Adv. Agron. 74:1-40.

Karlen, D.L., M.J. Mausbach, J.W. Doran, R.G. Cline, R.F. Harris, and G.E. Schuman. 1997. Soil quality: A concept, definition, and framework for evaluation. Soil Sci. Soc. Am. J. 61:4-10.

Kennedy, A.C., and R.I. Papendick. 1995. Microbial characteristics of soil quality. J. Soil Water Conserv. 50:243-248.

Kessavalou, A., and D.T. Walters. 1997. Winter rye as a cover crop following soybean under conservation tillage. Agron. J. 89:68-74.

Khanna, P.K., B. Ludwig, J. Bauhaus, and C. O'Hara. 2001. Assessment and significance of labile C pools in forest soils. p. 167-182. *In* R. Lal, J.M. Kimble, R.F. Follett, and B.A. Stewart (ed.) Assessment methods for soil carbon. Lewis Publishers, Boca Raton, FL.

Kravchenko, A.N., and D.G. Bullock. 2000. Correlation of corn and soybean grain yield with topography and soil properties. Agron. J. 92:75-83.

Kuo, S., Sainju, U.M., and E.J. Jellum. 1997. Winter cover crop efects on soil organic carbon and carbohydrate in soil. Soil Sci. Soc. Am. J. 61:145-152.

Lal, R. 1998a. Basic concepts and global issues: Soil quality and agricultural sustainability. p. 3-12. *In* R. Lal (ed.) Soil quality and agricultural sustainability. Ann Arbor Press, Chelsea, MI.

Lal, R., J. Kimble, R. Follett, and C.V. Cole, 1998b. Potential of U.S. Cropland for Carbon Sequestration and Greenhouse Effect Mitigation. Sleeping Bear Press, Chelsea, MI, USA.

Lal, R., J.M. Kimble, and R.F. Follett. 2001. Methodological challenges toward balancing soil C pool and fluxes. p. 659-668. *In* R. Lal, J.M. Kimble, R.F. Follett, and B.A. Stewart (ed.) Assessment methods for soil carbon. Lewis Publishers, Boca Raton, FL.

Lal, R, T.M. Sobecki, T. Iivari, and J.M. Kimble. 2004. Soil degradation in the United States: Extent, Severity, and Trends. Lewis Publishers, Boca Raton, FL.

Larson W.E., and F.J. Pierce. 1991. Conservation and enhancement of soil quality evaluation for sustainable land management in the developing world. p. 175-203. *In* Evaluation for sustainable land management in the developing world. Int. Board Soil Res. and Management (IBSRAM). Proc. 12 (Vol. 2). Bangkok, Thailand.

Larson W.E., and F.J. Pierce. 1994. The dynamics of soil quality as aa measure of sustainable management. p. 37-51. *In* J.W.Doran, D.C. Coleman, D.F. Bezdicek, and B.A. Stewart (ed.) Defining soil quality for a sustainable environment. SSSA Spec. Publ. 35. SSSA, Madison, WI.

Lefroy, R.D.B, G.J. Blair, and W.M. Strong. 1993. Changes in soil organic matter as measured by organic carbon fractions and ^{13}C isotope abundance. Plant Soil 155/156:399-402.

Liebig, M. and J Doran. 1999. Evaluation of farmer's perceptions of soil quality indicators. Am. J. Altern. Agric. 14:11-21.

Liang, B.C., A.F. Mackenzie, M. Schnitzer, C.M. Monreal, P.R. Voroney, and R.P. Beyaert. 1998. Management-induced change in labile soil organic matter under continuous corn in eastern Canadian soils. Biol. Fertil. Soils 26:88-94.

Loginow, W., W. Wisniewski, S.S. Gonet, and B. Ciescinska. 1987. Fractionation of organic carbon based on susceptibility to oxidation. Polish J. Soil Sci. 20:47-52.

Loveland, P., and J. Webb. 2003. Is there a critical level of organic matter in agricultural soils of temperate regions: A review. Soil Tillage Res. 70:1-18.

Maddonni, G.A., S. Urricariet, C.M. Ghersa, and R.S. Lavado. 1999. Assessing soil quality in the Rolling Pampa, using soil properties and maize characteristics. Agron. J. 91:280-287.

Magdoff, F. 1992. Building soils for better crops: Organic matter management. Univ. of Nebraska Press, Lincoln, NE.

Magdoff, F. 1996. Soil organic matter fractions and implications for interpreting soil organic matter tests. p. 11-19. *In* F.R. Magdoff, M.A. Tabatabai, and E.A. Hanlon, Jr. (ed.) Soil organic matter: Analysis and interpretation. SSSA Spec. Publ. 46. SSSA, Madison, WI.

Magdoff, F., and R.R. Weil. 2004. Soil organic matter management strategies. p. 45-65. *In* F. Magdoff and R.R. Weil (ed.) Soil organic matter in sustainable agriculture. CRC Press. Boca Raton, FL.

Majchrzak, R.N., K.N. Olson, G. Bollero, and E.D. Nafziger. 2001. Using soil properties to predict wheat yields on Illinois soils. Soil Sci. 166:267-280.

Marumoto, T., J.P. Anderson, and K.H. Domsch. 1982. Mineralization of nutrients from soil microbial biomass. Soil Biol. Biochem. 14:469-475.

Martens, D.A., and W.T. Frankenberger, Jr. 1992. Decomposition of bacterial polymers in soil and their influence on soil structure. Biol. Fertil. Soils 13:65-73.

McCracken, D.V., S.J. Corak, M.S. Smith, W.W. Frye, and R.L.Blevins. 1989. Residual effects of nitrogen fertilization and winter cover cropping on nitrogen availability. Soil Sci. Soc. Am. J. 53:1459-1464.

McGill, W.B., H.W. Hunt, R.G. Woodmansee, and J.O. Reuss. 1981. PHOENIX, a model of the dynamics of carbon and nitrogen in grassland soils. Ecol. Bull. (Stockholm) 33:49-115.

McGill, W.B., K.R. Cannon, J.A. Robertson, and F.D. Cook. 1986. Dynamics of soil microbial biomass and water soluble C in Breton L after 50 years of cropping to two rotations. Can. J. Soil Sci. 66:1-19.

Melsted, S.W. 1954. New concepts of management of Corn Belt soils. Adv. Agron. 6:121-142.

Mendes, I.C., A.K. Bandick, R.P. Dick, and P.J. Bottomley. 1999. Microbial biomass and activities in soil aggregates affected by winter cover crops. Soil Sci. Soc. Am. J. 63:873-881.

Monreal, C.M., R.P. Zentner, and J.A. Robertson. An analysis of soil organic matter dynamics in relation to management, erosion and yield of wheat in long term crop rotation plots. Can. J. Soil Sci. 77:553-563.

Moody, P.W., S.A. Yo, and R.L. Aitken. 1997. Soil organic carbon, permanganate fractions, and the chemical properties of acidic soils. Aust. J. Soil Res. 35:1301-1308.

Morin, J., and J. van Winkel. 1996. The effect of raindrop impact and sheet erosion on infiltration ate and crust formation. Soil Sci. Soc. Am. J. 60:1223-1227.

N'Dayegamiye, A., and T.S. Tran. 2001. Effects of green manures on soil organic matter and wheat yields and N nutrition. Can. J. Soil Sci. 81:371-382.

Ndiaye, E.L., Sandeno, J.M., McGrath, D. and R.P. Dick. 2000. Integrative biological indicators for detecting change in soil quality. Am. J. Alt. Agric. 15:26-36.

Needelman, B.A., M.M. Wander, G.A. Bollero, C.W. Boast, G.K. Sims, and D.G. Bullock. 1999. Interaction of tillage and soil texture: Biologically active soil organic matter in Illinois. Soil Sci. Soc. Am. J. 63:1326-1334.

Oades, J.M. 1984. Soil organic matter and structural stability: Mechanisms and implications for management. Plant Soil 76:319-337.

Odland, T.E., and H.C. Knoblauch. 1938. The value of cover crops in continuous corn culture. J. Am. Soc. Agron. 30:22-29.

Ortega, R.A. G.A. Peterson, and D.G. Westfall. 2002. Residue accumulationand changes in soil organic matter as affected by cropping intensity in no-till dryland agroecosystems. Agron J. 94:944-954.

Pagliai, M., and L.V. Antisari. 1993. Influence of waste organic matter on soil micro- and macrostructure. Bioresource Tech. 43:205-213.

Parr J.F., R.I. Papendick, S.B. Hornik, and R.E. Meyer. 1992. Soil quality: Attributes and relationship to alternative and sustainable agriculture. Am. J. Alt. Agric. 7:5-10.

Parton, W.J., D.S. Schimel, C.V. Cole, and D.S. Ojima. 1987. Analysis of Factors Controlling Soil Organic Matter Levels in Great Plains Grasslands. Soil Sci. Soc. Am. J. 51:1173-1179.

Parton W.J., and P.E. Rasmussen. 1994. Long term effects of crop management in wheat-fallow: II. CENTURY model simulations. Soil Sci. Soc. Am. J. 58:530-536.

Paul, E.A., and J. Van Veen. 1978. The use of tracers to determine the dynamic nature of organic matter. Trans. Int. Congr. Soil Sci., 11th 3:61-102.

Paul, E.A. 1984. Dynamics of organic matter in soils. Plant Soil 76:275-285.

Paustian, K., W.J. Parton, and J. Persson. 1992. Modeling soil organic matter in organic-amended and nitrogen-fertilized long term plots. Soil Sci. Soc. Am. J. 56:476-488.

Paustian, K. H.P. Collins, and E.A. Paul. 1997a. Management controls on soil carbon. p. 15-49. *In* E.A. Paul, K. Paustian, E.T. Elliot, and C.V. Cole (ed.) Soil organic matter in temperate agroecosystems. CRC Press, Boca Raton, FL.

Paustian, K., O. Amdren, H.H. Janzen, R. Lal, P. Smith, G. Tian, H. Tiesssen, M. Van Noordwijk, and P.L. Woomer. 1997b. Agricultural soils as a sink to mitigate CO_2 emissions. Soil Use Manage. 13:230-244.

Pieri, C.J.M.G. 1992. Fertility of soils: A future for farming in the West African Savannah. Springer-Verlag, Berlin.

Potter, K.N., H.A. Tolbert, O.R. Jones, J.E. Matocha, J.E. Morrison, and P.W. Unger. 1998. Distributionan amount of soil organic C in long-term management systems in Texas. Soil Tillage Res. 47:309-321.

Puget, P. and L.E. Drinkwater. 2001. Short-term dynamics of root and shoot derived carbon from a leguminous green manure. Soil Sci. Soc. Am. J. 65:771-779.

Pulleman, M.M., J Bouma, E.A. van Essen, and E.W. Meijles. 2000. Soil organic matter content as a function of different land use history. Soil Sci. Soc. Am. J. 64:689-693.

Raimbault, B.A., T.J. Vyn, and M. Tollenaar. 1990. Corn Response to rye cover crop management and spring tillage systems. Agron. J. 82:1088-1093.

Raimbault, B.A., T.J. Vyn, and M. Tollenaar. 1991. Corn response to rye cover crop, tillage methods, and planter options. Agron. J. 83:287-290.

Rasiah, V., and B.D. Kay. 1995. Runoff and soil loss as influenced by selected stability parameters and cropping and tillage practices. Geoderma 68:321-329.

Rasmussen, P.E., and W.J. Parton. 1994. Long-term effects of residue management in wheat-fallow: I. Inputs, yield, and soil organic matter. Soil Sci. Soc. Am. J. 58:523-530.

Römkens, P.F.A.M., J. van der Plicht, and J. Hassink. 1999. Soil organic matter dynamics after the conversion of arable land to pasture. Biol. Fertil. Soils 28:277-284.

Ruttan, V.W. 1999. The transition to agricultural sustainability. Proc. National Acad. Sci. 96:5960-5967.

Sainju, U.M., B.P. Singh, and W.F. Whitehead. 2000. Cover crops and nitrogen fertilization effects on soil carbon and nitrogen and tomato yield. Can. J. Soil Sci. 80:523-532.

Sainju, U.M., B.P. Singh, and W.F. Whitehead. 2001. Comparison of the effects of cover crops and nitrogen fertilization on tomato yield, root growth and soil properties. Scientia Horticulturae 91:2001-214.

Salinas-Garcia, J.R., F.M. Hons, and J.E. Matocha. 1997. Long-term effects of tillage and fertilization on soil organic matter dynamics. Soil Sci. Soc. Am. J. 61:152-159.

Seybold, C.A., M.J. Mausbach, D.L. Karlen, and H.H. Rogers. 1996. Quantification of soil quality. p.53-68. *In* T.S.Q. Intitute (ed.) The soil quality concept. USDA/NRCS, Washington, D.C.

Shang, C., and H. Tiessen. 1997. Organic matter lability in tropical Oxisol: Evidence from shifting cultivation, chemical oxidation, particle size, and magnetic fractionations. Soil Sci. 162:795-807.

Sikora, L.J., and D.E. Stott. 1996. Soil Organic Carbon and Nitrogen. p. 157-167. *In* J.W.Doran and A.J. Jones (ed.) Methods for assessing soil quality. SSSA Spec. Publ. 35. SSSA, Madison, WI.

Six, J., K. Paustian, E.T. Elliot, and C. Combrink. 2000. Soil structure and organic matter: I. Distribution of aggregate size classes and aggregate-associated carbon. Soil Sci. Soc. Am. J. 64:681-689.

Six, J., R.T. Conant, E.A. Paul, and K. Paustian. 2002. Stabilization mechanisms of soil orgainc matter: implications for C-saturation of soils. Plant Soil 241:155-176.

Skoog, D.A., and D.M. West. 1969. Applications of oxidation-reduction reagents to volumetric organic analysis. Chapter 21. *In* Fundamentals of Analytical Chemistry. 2nd Edition. Holt, Rinehart, and Winston, New York, NY.

Smith, M.S., W.W. Frye, and J.J. Varco. 1987. Legume winter cover crops. Adv Soil Sci. 7:95-139.

Sparling, G., M. Vojvodić-Vuković, and L.A Schipper. 1998. Hot-water-soluble C as a simple measure of labile soil organic matter: the relationship with microbial biomass C. Soil Biol. Biochem. 30:1469-1472.

Soil Science Society of America. 2001. Internet glossary of soil science terms [Online]. Available by the Soil Science Society of America at www.soils.org/sssagloss, accessed 15 June 2004.

Stanford, G. 1978. Evaluation of ammonium release by alkaline ammonium extraction as an index of soil nitrogen availability. Soil Sci. 126:244-253.

Stanier, R.Y., M. Douderoff, and E.A. Adelberg. 1968. General microbiology. MacMillan, London.

Staver, K.W. and R.B. Brinsfield. 1990. Patternsof soil nitrate availability in corn production systems: Implications for reducing groundwater contamination. J. Soil Water Conserv. 45:318-323.

Steer, A. 1998. Making development sustainable. Adv. Geo-Ecol. 31:857-865.

Stevenson, F.J., and M.A. Cole. 1999. Cycles of soil: Carbon, nitrogen, phosphorus, sulphur, micronutrients. John Wiley & Sons Inc., New York.

Stine, M.A., and R.R. Weil. 2002. The relationship between soil quality and crop productivity across three tillagesystems in south central Honduras. Am. J. Altern. Agric. 17:2-8.

Strickling, E. 1975. Crop sequences and tillage in efficient crop production. p. 20-29 *In* Agron. Abstr. American Society of Agronomy, Madison, WI.

Studdert, G.A., and H.E. Echeverría. 2000. Crop rotations and nitrogen fertilization to manage soil organic carbon dynamics. Soil Sci. Soc. Am. J. 64:1496-1503.

Studdert, G.A., H.E. Echeverria, and E.M. Casanovas. 1997. Crop-pasture rotation for sustaining the quality and productivity of a Typic Argiudoll. Soil Sci. Soc. Am. J. 61:1466-1472.

Syers, J.K., and E.T. Craswell. 1995. Role of soil organic matter in sustainable agricultural systems. p. 7-14. *In* R.D.B. Lefroy, G.J. Blair, and E.T. Craswell (ed.) Soil organic matter management for sustainable agriculture: A workshop held in Ubon, Thailand, 24-26 August 1994. ACIAR Proceedings No. 56, Australian Center for International Research, Canberra, Australia.

Tabatabai, M.A. 1996. Soil organic matter testing: An overview. p. 1-9. *In* F.R. Magdoff, M.A. Tabatabai, and E.A. Hanlon, Jr. (ed.) Soil organic matter: Analysis and interpretation. SSSA Spec. Publ. 46. SSSA, Madison, WI.

Tiessen, H., E. Cuevas, and P. Chacon. 1994. The role of soil organic matter in sustaining soil fertility. Nature 371:783-785.

Tirol-Padre, A., and J.K. Ladha. 2004. Assessing the reliability of permanganate-oxidizable carbon as an index of soil labile carbon. Soil Sci. Soc. Am. J. 68:969-978.

Tisdall, J.M., and J.M. Oades. 1982. Organic matter and water stable aggregates in soils. J. Soil Sci. 33:141-163.

Torbert, H.A., D.W. Reeves, and R.L. Mulvaney. Winter legume cover crop benefits to corn: rotation vs. fixed-nitrogen effects. Agron J. 88:527-535.

Unger, P.W. 1982. Surface soil physical properties after 36 years of cropping to winter wheat. Soil Sci. Soc. Am. J. 46:796-801.

USDA-NRCS. 1998. Soil quality test kit guide. Soil Quality Institute, Natural resources Conservation Service, United States Department of Agriculture, Lincoln, NE and Washington DC.

Utomo, M., W.W. Frye, and R.L. Blevins. 1990. Sustaining soil nitrogen for corn using hairy vetch cover crop. Agron. J. 82:979-983.

Vance, E.D., P.C. Brookes, and D.S. Jenkinson. 1987. An extraction method for measuring soil microbial biomass C. Soil Biol. Biochem. 19:703-707.

Van Doren, D.M., Jr., Triplett, G.B., Jr., and J.E. Henry. 1976. Influence of long-term tillage, crop rotation, and soil type combinations on corn yields. Soil Sci. Soc. Am. J. 40:100-105.

Vaughan, J.D. and G.K. Evanylo, 1998. Corn response to cover crop species, spring desiccation time, and residue management. Agron. J. 90:536-544.

Wagger, M.G., M.L. Cabrera, and N.N. Rannels. 1998. Nitrogen and carbon cycling in relation to cover crop residue quality. Soil Water Cons. 53:214-224.

Walkley A., and I.A. Black. 1947. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Sci. 37:29-38.

Wander, M.M., S.J. Traina, B.R.Stinner, an S.E. Peters. 1994. Organic and conventional management effects on biologically active soil organic matter pools. Soil Sci. Soc. Am. J. 8:1130-1139.

Wander, M.M., M.G. Bidart, and S. Aref. 1998. Tillage impacts on depth distribution of total and particulate organic matter in three Illinois soils. Soil Sci. Soc. Am. J. 62:1704-1711.

Wander, M.M., and G.A. Bollero. 1999. Soil quality assessment of tillage impacts in Illinois. Soil Sci. Soc. Am. J. 63:961-971.

Wander, M.M., and L.E. Drinkwater. 2000. Fostering soil stewardship through soil quality assessment. Appl. Soil Ecol. 15:61-73.

Wander M.M., and X.M. Yang. 2000. Influence of tillage on the dynamics of loose- and occluded-particulate organic and humified organic matter fractions. Soil Biol. Biochem. 32:1151-1160.

Wander M.M. 2004. Soil organic matter fractions and their relevance to soil function. p. 67-102. *In* F. Magdoff and R.R. Weil (ed.) Soil organic matter in sustainable agriculture. CRC Press. Boca Raton, FL.

Warkentin, B.P. 1995. The changing concept of soil quality. J. Soil Water Conserv. 50:226-228.

Weil, R.R., K.A. Lowell, and H.M. Shade. 1993. Effects of intensity of agronomic practices on a soil ecosystem. Am. J. Altern. Agric. 8:5-14.

Weil, R.R., K.R. Islam, M.A. Stine, J.B. Gruver, and S.E. Samson-Liebig. 2003. Estimating active carbon for soil quality assessment: A simplified method for labd and feld use. Am. J. Altern. Agric. 18:3-17.

Weil, R.R., and F. Magdoff. 2004. Significance of soil organic matter to soil quality and health. p. 1-43. *In* F. Magdoff and R.R. Weil (ed.) Soil organic matter in sustainable agriculture. CRC Press. Boca Raton, FL.

Weinhold, B.J., and D.L. Tanaka. 2001. Soil property changes during conversion from perrenial vegetation to annual cropping. Soil Sci. Soc. Am. J. 65: 1795-1803.

Whitbread, A.M., G.J. Blair, and R.D.B. Lefroy. 2000. Managing legume leys, residues and fertilisers to enhance the sustainability of wheat cropping systems in Australia 2. Soil physical fertility and carbon. Soil Tillage Res. 54:77-89.

Wilson, D.O., and W.L. Hargrove. 1986. Release of nitrogen from crimson clover residue under two tillage systems. Soil Sci. Soc. Am. J. 50:1251-1254.

Wood, C.W., D.G. Westfall, and G.A. Peterson. 1991. Soil carbon and nitrogen changes on intiation of no-till cropping systems. Soil Sci. Soc. Am. J. 55:470-476.

Zsolnay, A., and H. Gorlitz. 1994. Water extractable soil organic matter in arable soils: Effects of drought and long-term fertilization. Soil Biol. Biochem. 26:1257-1261.

CHAPTER TWO

Labile Carbon Test for Predicting Response to Improved Organic Matter Management. I: Crop Responses

INTRODUCTION

Soil properties related to soil organic matter (SOM) can serve as important indicators of soil quality (Arshad and Coen, 1992; Gregorich et al., 1994; Larson and Pierce, 1994; Kennedy and Papendick, 1995; Wander and Bollero, 1999; Ndiaye et al., 2000; Islam and Weil, 2000; Wander and Drinkwater, 2000). Soil organic matter is a difficult to quantify, heterogeneous mixture of organic compounds. Measurements of SOM are usually estimated by measuring its dominant component: total soil organic carbon (SOC). Soil organic C varies across topography, climatic regions, and soil types. The bulk of SOC is comprised of highly recalcitrant humified substances that are slow to accumulate or degrade. Therefore, the effects of contrasting soil management practices may take many years to become apparent in measurements of total SOC (Sikora and Stott, 1996; Weil et al., 2003).

The fraction of total SOC that is microbially labile is frequently referred to as active SOC. Active SOC is a small component of total SOC, but it plays a major role in maintaining soil quality (Weil, 1992). It is directly related to mineralization and availability of soil C, N (Alvarez et al., 1998; Gunapala and Scow, 1998), S (Banerjee and Chapman, 1996), and P (Jenkinson and Ladd, 1981; Marumoto et al., 1982). This pool of SOC is also associated with soil aggregate stabilization (Tisdall and Oades, 1982).

Evaluation of management practices designed to improve soil quality requires indicators that rapidly respond to soil management. Measurements related to active pool SOC have shown such sensitivity. These measurements include microbial biomass C (Kenedy and Papendick, 1995; Islam and Weil, 2000), microbial biomass N (Jenkinson, 1988a), mineralizable C, mineralizable N (Gregorich et al., 1994), microbial enzymatic activity (Dick, 1992; Ndiaye et al., 2000), particulate organic matter (Cambardella and Elliot, 1992; Wander and Bidart, 2000), light fraction organic matter (Christensen, 1992; Wander et al., 1994) and soil carbohydrates measured as anthrone-reactive C (Deluca and Keeny, 1993; Saviozzi et al., 1999).

Scientists, farmers, and extension agents need soil quality assessment tools at the field level that can facilitate soil management decisions (Liebig and Doran, 1999; Wander and Drinkwater, 2000). The USDA Natural Resources Conservation Service (NRCS) has developed a soil quality test kit (USDA-NRCS, 2003) for field assessment of soil quality. This kit currently tests nine soil quality parameters but it does not include a suitable test for SOC. The absence of a SOC test is mainly due to the insensitivity of these tests in detecting management induced changes in total SOC over the short term and the fact that a practical total SOC test that can be conducted in the field has not been developed. Total SOC tests require acid digestions or combustion at high temperatures while soil parameters commonly used to represent active SOC involve extensive incubations or sieving processes.

A recent method for quantifying active SOC involves oxidizing labile organic C (C_L) by exposing it to a known concentration of $KMnO_4$ and subsequently measuring via spectrophotometer the change in $KMnO_4$ concentration due to reaction with C_L (Lefroy et

al., 1993; Blair et al., 1995; Moody et al., 1997; Bell et al., 1999; Weil et al., 2003). Most C_L research done with $KMnO_4$ oxidation has employed the method developed by Blair et al., (1995). Weil et al., (2003) modified and simplified the Blair et al., (1995) method making it more sensitive to C_L and suitable for use in both laboratory and in field settings.

Weil et al. (2003) used a 0.02*M* $KMnO_4$ solution (as opposed to the 0.333*M* solution used by Blair et al., 1995), and found this solution to be reactive with only the most labile forms of soil C. The solution used by Blair et al. (1995) reacts with a larger fraction of soil C, including some recalcitrant C (Lefroy et al., 1993; Weil et al., 2003). Weil et al. (2003) also made the $KMnO_4$ solution in 0.1*M* $CaCl_2$ to promote flocculation and causing the soil to settle after shaking, eliminating the need for centrifugation and making the procedure practical in the field.

Weil et al. (2003) found the 0.02*M* $KMnO_4$ oxidation method to be more sensitive to tillage treatments than total SOC and more closely correlated with other soil quality indicators (microbial biomass, microbial biomass C, basal respiration, and aggregate stability) than total SOC. They suggest that their method is a simple, repeatable means to estimate a biologically active C pool that is associated with soil quality and could aid farmers in their soil management decisions.

It has been difficult to demonstrate the direct influence of SOC on crop productivity. This is largely due the fact that SOC levels are usually related to environmental factors that include regional climate, topography, and soil texture (Dick and Gregorich, 2004). Evaluations of SOC effects on crop productivity across differing soils and regions are often confounded by the effects of these environmental factors.

Researchers evaluating SOC effects on crop yields often impose treatments on the soil such as crop rotations, tillage systems, or manure applications. Effects of SOC on crop yields can be obscured by other effects of imposed treatments, such as N inputs from legume residues or manure applications or structural effects of tillage.

Kravchenko and Bullock (2000) found that, of all parameters measured, SOC content had the most influence on corn (*Zea mays* L.) yield variability. This effect was greatest in soil types that had inherently low SOC levels. Majchrzak et al. (2001) and Alvarez et al (2002) found positive correlations between SOC level and wheat yield. Alvarez et al. (2002) also found light fraction organic matter and mineralizable N to be related to wheat yield variability. Stine and Weil (2002) found SOC to be predictive of macroaggregate stability and soil porosity across different tillage systems. They also found macroaggregate stability, along with C_L, to be highly correlated with crop productivity under different tillage regimes.

Diaz-Zorita et al. (1999) found that in soils having SOC levelslower than 42 Mg/ha in the A horizon, every 1.0 Mg ha^{-1} loss of SOC was associated with a 40 kg ha^{-1} reduction in wheat yield Bauer and Black (1994) observed that in soils having SOC contents ranging from 64 to 142 Mg ha^{-1}, every additional 1.0 Mg ha^{-1} of SOC was equivalent to an increase of 35.2 kg ha^{-1} of aboveground dry biomass and 15.6 kg/ha of wheat grain yield.

Strickling (1975), as cited in Weil and Magdoff (2004), successfully isolated SOC effects on crop yields by imposing crop rotations to alter SOC over 20 years. All plots were treated alike (including fertilizer application) in the final years of the experiment and the residual effects of increased or depleted SOC were assessed.

Strickling (1975) found that SOC levels accounted for 82-84% of the variation in corn yields. These effects were independent of N fertilization levels. According to Strickland (1975), SOC influenced crop yields through enhanced water infiltration that resulted from better aggregation in high SOC plots.

Little research has explored the concept of using a SOC measurement to identify soils where productivity may increase in response to improved SOC management practices. Greer and Schoenau (1997) and Carter et al. (2004) discuss assessment frameworks that incorporate SOC into prediction of soil quality and soil prductivity. These frameworks are quite complex, involving multiple measurements and determinations. Their use to guide management decisions for individual fields may not be practical. Many papers suggest using SOC or active pool SOC components to assess or monitor management induced changes in soils (LeFroy et al., 1993; Biederbeck et al., 1994; Gregorich et al., 1994; Ellert and Bettany, 1995; Salinas-Garcia et al., 1997; Campbell et al., 1999; Bowman et al., 1999; Maddonni et al., 1999; Ndiaye et al., 2000 and others). Most of these works focus on soil quality monitoring for sustainability and do not directly propose using these tests to identify soils where improved management could lead to improved productivity.

Some studies have implied, but not directly proposed, using SOC parameters to predict whether a soil's quality and productivity could benefit from improved SOC management. Bruce et al. (1995) found SOC in the A horizon to be the manageable soil component that significantly influenced crop available water and reduced erosion. In their study degraded soils were characterized by low levels of SOC and had fewer water stable aggregates, low rates of infiltration, and low crop biomass production. They

observed that restoration and maintenance of soil productivity was associated with maintenance of a decomposing mulch layer on the soil surface. Tiessen et al. (1994) suggested that in many tropical soils, the quantification of SOC cycling might be an important guide to assessing agricultural potential. Other studies attempt to quantify SOC with the goal of minimizing losses (Bauer and Black, 1994; Bruce et al., 1995; Shang and Tiessen, 1997; Diaz-Zorita et al., 1999). Loveland and Webb (2003) searched the literature for evidence of a minimum level of SOC below which soil productivity declines, but they concluded that no such critical level exists.

One management practice that can be used to increase SOC is the planting of winter cover crops. High biomass winter cover crops, such as winter rye (*Secale cereal* L.) and annual ryegrass (*Lolium multiflorum* Lam.) provide substantial C inputs to soil because of the above- and belowground residues they produce. Kuo et al. (1997) estimated rye dry biomass at Feekes growth stage 8 (Large, 1954) to be 4.4 Mg ha^{-1} aboveground and 5 Mg ha^{-1} belowground to a depth of 20cm. Over 6 years Kuo et al. (1997) saw a small, but detectable, increase (0.5-1.0 g kg^{-1}) in total SOC where rye residues were incorporated via rototilling. In a six year study, Wagger et al. (1998) also observed increased total SOC associated with winter rye cover crops in the temperate humid region of Washington.

Cover crops frequently are observed to affect soil parameters related to active pool SOC. The positive influence of rye or other cereal winter cover crops has been observed in microbial biomass C (Hu et al., 1997; Mendes et al., 1999; Ndiaye et al., 2000), mineralizable C (Mendes et al., 1999; Sainju et al., 2000), mineralizable N

(Mendes et al., 1999), particulate organic matter (Hu et al., 1997), soil enzymes (Ndiaye et al., 2000) and aggregate stability (Hermawan and Bomke, 1997; Gruver, 1999).

While the use of cover crops to enhance soil productivity has recently been regaining acceptance (Hu et al., 1997), this concept is not new. Odland and Knoblauch (1938) found that fields treated with rye or leguminous cover crops showed increased yields in both corn stover and grain over fields not treated with cover crops. Most studies reporting yield effects in crops grown after winter cover crops deal with N inputs from leguminous cover crops (Odland and Knoblauch, 1938; Smith et al., 1987; Blevins et al., 1990; Utomo et al., 1990; Torbert et al., 1996; Vaughan and Evanylo, 1998; Sainju et al., 2000; N'Dayegamiye and Tran, 2001; Sainju et al., 2001). Information on C input related yield effects following winter cover crops is scarce.

The literature available on effects of rye cover crops on yields of subsequent cash crops is inconclusive. Odland and Knoblauch (1938) attributed yield increases to increased water holding capacity in rye treated fields. In a study comparing winter rye treated plots to winter fallow plots, Kabir and Koide (2002) attributed higher yields of sweet corn on rye treated plots to enhanced P uptake in corn as a result of increased mycorrhizal activity in rye treated plots. Bauer and Busscher (1996) found higher cotton lint yields in rye treated fields than in fields left fallow. McCracken et al. (1989) did not see significant yield effects in crops that followed rye. Other studies reported thatrye mulch on fields reduced crop yields by inhibiting crop emergence (Eckert, 1988). Yield reductions due to possible allelopathic effects of rye have also been reported (Raimbault et al., 1990; Kessavalou and Walters, 1997).

Labile soil C could serve as an early indicator of management-induced changes in SOC content. It may also be useful in identifying soils where soil productivity could be enhanced with improved SOC management practices. The present study was undertaken to determine if the Weil et al. (2003) procedure can be used as a soil test to ascertain where ecological functions are most likely to respond to improved SOC management practices, such as the use of winter cover crops. The expected responses include enhancements in such soil quality functions as crop productivity, water infiltration, erosion resistance and nutrient cycling.

In this paper we investigated crop responses to the soil organic matter management practice of growing a winter rye cover crop. We hypothesized that all else being equal, a field that tests lower in C_L will benefit more (show more of an increase in crop productivity and soil functional responses) from improved organic matter management practices (use of winter cover crops in this case), than will a field that tests higher in C_L.

MATERIALS AND METHODS

Establishment of the Experiment

The experiment was initiated in fall 2001 at four sites. The site locations were at the University of Maryland Research and Education Centers at Beltsville, Upper Marlboro, and Keedysville, MD and at Cedar Meadow Farm, Holtwood, PA. At each site paired fields consisting of similar soils but contrasting management history (MH) were identified and divided into 4 blocks, each containing one plot with and one plot without a rye cover crop.

Soil survey classification and taxonomic similarity between the fields at each site (Table 2.1) was initially evaluated with county soil surveys report data (Matthews, 1962; Kirby et al., 1967; Custer, 1985). Soil similarity between fields was further verified by field description of auger borings along transects within each field. In each field, profile descriptions were made at 6.25, 25, and 43.75m along each of two 50m transects, spaced 12.6m apart and following the length of the field . Soil color, texture, and redoximorphic features were described to a 90cm depth (see Table 2.2). Samples from the A horizon were collected and subsequently analyzed for particle size determination using a modified pipette method (Table 2.1). The experimental plots in each field were then blocked along gradients of topography and clay content.

The experimental portion of each field measured 48.64m by 12.16m at Beltsville, Keedysville, and Upper Marlboro. See Figure 2.1 for an example of a typical field layout.. At Holtwood, the plots had been established in 1998, prior to their use in this study and the experimental field dimensions were 36.60m by 36.48m.

At each site, one field had a MH of long-term crop production (MH_{crop}) with conventional tillage and the other field had a MH of long-term continuous sod (MH_{sod}). The duration of these management regimes for each site are given in Table 2.3. Differences in MH were determined through farmer interviews and farm records. The fields were sampled to 15cm using a fully enclosed, zero contamination, soil probe (JMC Soil Probes, Clements Associates, Inc., Newton, IA) and tested for pH and total SOC (Northeast Coordinating Committee on Soil Testing ,1995) at the University of Maryland Soil Testing Laboratory (Table 2.1).

In October, 2001, the sod at Keedysville and Upper Marlboro was sprayed with paraquat (N,N'-dimethyl-gamma,gamma'-bipyridylium dichloride) at a rate of 1.05 kg a.i. ha^{-1} and no-till crop production was initiated. This treatment was not necessary at Beltsville and Holtwood because the MH_{sod} fields at these sites had already been converted to crop production when this study was initiated.

Implementation of Soil Organic Matter Management: Cover Crops

During the course of this experiment no-till management was used for all fields. At Beltsville, Keedysville, and Upper Marlboro, each field was divided into four blocks measuring 12.60m by 12.60m. These blocks were then subdivided into subplots that measured 12.60m by 6.8m. At Holtwood the blocks and subplots had been established prior to this study in 1998. Blocks at Holtwood measured 36.60m by 9.12m. Holtwood subplots measured 36.60m by 4.56m. At Beltsville, Keedysville, and Upper Marlboro, subplots within each block were randomly assigned one of two possible winter cover crop treatments: rye cover crop or bare (no cover crop). To simplify operations for the commercial farmer at Holtwood, the subplots were long strips with adjacent strips alternating systematically between rye and no-rye treatments. Because of this systematically alternating treatment arrangement, all dependent variables were examined for systematic behavior by plotting dependent variables along the spatial gradient. No systematic variance was observed

At each site cover crop treatments were planted in fall 2001 and fall 2002 after the main (summer) crop was harvested. Rye planting dates are shown in Table2.4 .

All fields were amended with P and K fertilizer and lime in late March 2002, according to recommendations based on the Maryland Soil Test Lab results. At Upper Marlboro, soil pH prior to lime application was low enough (4.7 on sod and 5.2 on MH_{crop} fields) that the rye cover crop may have been affected. Also, at both Upper Marlboro and Keedysville, soil P levels were low enough prior to fertilization to possibly have limited the first rye cover crop. Cover crops were killed in spring 2002 and spring 2003 through application of glyphosate [(N-phosphonomethyl) glycine] applied at a rate ranging from 1155 g a.i. ha^{-1} to 1542 g a.i. ha^{-1} (Table 2.4). Cover crop stands differed between sites depending on the date on which rye was killed (Table 2.4). Excessive wetness at Upper Marlboro in fall 2002 – spring 2003 (Figure 2.2) killed the rye planted at this site and biomass estimates were not obtainable.

Immediately prior to the killing of cover crops above- and belowground cover crop biomass was measured at each site. Cutting as close to the soil surface as possible, all shoot biomass was harvested and weighed to the nearest 0.5g within two random $0.25m^2$ areas within each subplot. Samples for each subplot were then oven dried for four days at 60° C, weighed to the nearest 0.5g, and dry matter biomass was calculated for the entire plot area.

Belowground (root) biomass was estimated by collecting a 1900 cm^3 core of soil to 7.5 cm depth from areas where shoot biomass was removed. Roots were removed from soil cores by sectioning the core and placing the sections into a 2mm sieve nested above a 1mm sieve. The soil was washed from the roots while roots were caught in the nest of sieves. Roots were hand-separated from coarse mineral fragments, removed from the sieves, placed in paper bags, dried for four days at 60° C and weighed to the nearest

0.01 g. An estimate of root biomass within the 0-7.5cm depth was then calculated for the entire area of the subplot and this value used to calculate the shoot:root ratio.

Even though weed biomass on bare plots was very small compared to rye biomass, selected bare plots were sampled for above- and belowground weed biomass, similar to the method described for rye. Weed biomass estimates were not done at Beltsville and Upper Marlboro in spring 2002 because weed growth was negligible on bare plots at those sites due to treatment of bare plots with 1155 g a.i. ha^{-1} glyphosate in mid-March. Upper Marlboro weed growth was not measured in spring 2003 because weeds were killed by the excessive wetness already described for that site.

Because wet conditions at Upper Marlboro in spring 2003 precluded a normal cover crop treatment, this site was excluded from all analyses of effects and responses for 2003.

Implementation of Main Crops

Corn or soybean (*Glycine max* M.) crops were planted at all sites after rye was killed (Table 2.4). Corn and soybean rows were spaced 76 cm and 18 cm apart, respectively. Corn and soybeans were seeded at rates of 11,220 seeds ha^{-1} and 56,700 seeds ha^{-1}, respectively. When soybeans were planted, seed was inoculated with appropriate *Rhizobium*. In 2002 corn (Pioneer 34M94) was grown at Beltsville, Keedysville, and Upper Marlboro while Holtwood produced soybeans (Asgrow 4403). In 2003 Beltsville, Keedysville, and Upper Marlboro grew soybeans (Pioneer 93B68) while corn (Garst 848Bt) was planted at Holtwood. Corn received N fertilizer as indicated in Table 2.4. For the MH_{sod} field at Keedysville, P and K were also applied in

both 2002 and 2003 (Table 2.4), according to University of Maryland Soil Testing Lab recommendations.

During the summer drought in 2002 (Figure 2.2), supplemental irrigation was applied at Upper Marlboro and Holtwood, but no irrigation was available at Beltsville and Keedysville.

Main Crop Harvest Procedures I: Corn

Harvest dates are given in Table 2.4. Corn biomass and grain yields were estimated by harvesting 2 adjacent rows, each 6.08m long in the center of each plot. All ears of corn were removed from all plants in the harvest rows. Husks were left on the plant. Ears were weighed in the field to the nearest 0.01 kg. This weight was logged as the "plot green cobs, kg". From these ears a randomly selected subsample of 6 ears were weighed in the field to the nearest gram. The weight of this subsample was logged as the "sample green cobs, g". The subsample was placed in a cloth bag oven dried for 5 days at 60°C. All corn stalks in the harvest rows cut down. Stalks were cut as close to the ground as possible. Stalks were then weighed to the nearest 0.01 kg. This weight was logged as the "plot green stover, kg". From these stalks a representative subsample of 5 random stalks was taken. These stalks were broken up and weighed to the nearest gram. This weight was logged at the "sample green stover, g". Stover subsamples were placed in cloth bags and oven dried for 5 days at 60°C. After being oven dried, subsamples of cobs and stalks were re-weighed to the nearest gram. Oven-dry weights were recorded as "sample dry cobs, g" and "sample dry stover, g", respectively. The oven-dry grain was

then stripped from the cobs and weighed to the nearest gram. This weight was recorded as "sample dry grain, g". The amount of dry grain per harvest area was calculated as:

$$\text{Dry grain, kg} = \left(\frac{\text{sample dry grain, g}}{\text{sample green cobs, g}} \right) \times \text{plot green cobs, kg}$$

Grain moisture at harvest was calculated as:

$$\text{Grain moisture (\%)} = \left[\left(1 - \frac{\text{sample dry cobs, g}}{\text{sample green cobs, g}} \right) \right] \times 100$$

The amount of dry stover per harvest area was calculated as:

$$\text{Dry stover, kg} = \left(\frac{\text{sample dry stover, g}}{\text{sample green stover, g}} \right) \times \text{plot green stover, kg}$$

Stover and grain yield estimates in kg ha^{-1} for the entire plot were subsequently calculated. Whole plant biomass estimates were based on the sum of stover and grain yield estimates.

Main Crop Harvest Procedures II: Soybeans

In 2002 soybeans were the main crop at Holtwood and in 2003 they were grown at Beltsville, Upper Marlboro and Keedysville. Soybeans were harvested from two rows along a transect measuring 3.04m marked near the center of the plot. Plants were cut 1cm above the soil surface with pruning shears. Plants weighed to the nearest 0.01 kg and this weight was recorded as the "plot green whole plants, kg". From these plants a representative subsample of 10 plants was randomly collected and weighed to the nearest gram. This weight was recorded as the "sample green whole plants, g". Subsamples

were oven dried for 5 days at 60°C and weighed again to the nearest gram. This weight was recorded as the "sample dry whole plants, g". All beans within each subsample were then removed from their pods and weighed to the nearest gram. This weight was recorded as the "sample dry grain, g". The grain weight for the harvest area was calculated as:

$$\text{Dry grain, kg} = \left(\frac{\text{sample dry grain, g}}{\text{sample green whole plants, g}} \right) \times \text{plot green whole plants, kg}$$

The soybean stover weight for the harvest area was calculated as:

$$\text{Soybean Stover, kg} = \left(\frac{\text{sample dry whole plants, g}}{\text{sample green whole plants, g}} \right) \times \text{plot green whole plants, kg}$$

Whole plant moisture at time of harvest was calculated as:

$$\text{Whole plant moisture (\%)} = \left[1 - \left(\frac{\text{sample dry whole plant, g}}{\text{sample green whole plant, g}} \right) \right] \times 100$$

Stover and grain yield estimates in kg ha^{-1} for the entire plot were subsequently calculated. Whole plant biomass estimates were based on the sum of stover and grain yield estimates.

Estimation of Grain, Stover and Biomass Response to Cover Crop Treatment

Cash crop response to cover crop treatment (COVER) in blocks within management histories within each site (BLOCKS(MH(SITE))) was calculated for grain, stover and whole biomass. Blocks within (MH(SITE)) each contain one rye treated subplot and one bare subplot ($COVER_{rye}$ and $COVER_{bare}$). Crop response is a measurement of the difference between grain, stover, or biomass yields between $COVER_{rye}$ plots and $COVER_{bare}$ plots within each block. Crop response was calculated

by simply subtracting the dry grain, stover or biomass yield (kg ha^{-1}) in $COVER_{bare}$ plots within (BLOCKS(MH(SITE))) from the dry grain or biomass yield (kg ha^{-1}) in $COVER_{rye}$ plots within (BLOCKS(MH(SITE))). For analyses of relationships across all sites, responses within (BLOCKS(MH(SITE))) were converted to relative responses. Relative responses for grain, stover, and biomass were calculated as:

$$\text{Relative response, kg ha}^{-1} = \frac{\text{Yield in COVER}_{rye} - \text{Yield in COVER}_{bare}}{\text{Yield in COVER}_{bare}}$$

The use of relative responses allows response relationships to soil C parameters to be examined without being confounded by crop and site differences.

When analyzing the response relationships, across more than one site, with C_L or total soil C (C_T), the response parameter was tested directly against C_L or C_T measurements as well as the ratio of C_L or C_T to soil fine particle content ($C_{L/Fines}$ or $C_{T/Fines}$). Soil fine particle content was defined as percent clay plus percent silt. This was done because fine textured soils usually contain more SOC than coarse textured soils that have received similar organic inputs through time (Kortleven, 1963; Jenkinson, 1988b).

Collection of Weather Data

Both cover crop productivity and main crop productivity are related to climatic factors, particularly precipitation. Monthly temperature and precipitation data representative of the conditions at each site were based on reports from nearby weather stations. This data was collected for 2001, 2002, and 2003. Data for Beltsville, Upper Marlboro, and Holtwood was collected from monthly and annual climatological data reports for Maryland and Pennsylvania. Data for Beltsville was from the Beltsville

weather station. Data for Upper Marlboro came from the Upper Marlboro 3 NNW weather station. The closest weather station to the Holtwood site was at the Lancaster 2 NE Filtration Plant. These reports are produced by the National Climatic Data Center of the National Oceanic and Atmospheric Administration. These documents were accessed through the National Virtual Data System at http://www7.ncdc.noaa.gov/SerialPublications/index.html (NOAA-NCDC, 2001; 2002; 2003). Keedysville weather data was acquired from the Hagerstown Weather Station and was accessed at http://i4weather.net (Hagerstown Weather Station, 2001; 2002; 2003). Precipitation data for each site is presented in Figure 2.2.

Soil Sample Collection and Processing

Soil sampling at Holtwood was conducted on 15 Oct. 2001. AtKeedysville, Beltsville, and Upper Marlboro, the soil samples were collected on 16, 22, and 24 Jan. 2002, respectively. Soil samples were extracted with a fully enclosed, zero contamination soil probe (JMC Soil Probes, Clements Associates, Inc., Newton, IA) to a depth of 7.5 cm. This sampling depth was chosen because studies have shown that most of the impacts of no-till farming are seen in the shallowest sampling depths, near the rooting zone and crop residue inputs (Dick, 1983; Blevins et al., 1985; Dick et al., 1991; Potter et al. 1998). Soil was sampled within each subplot by taking 14 randomly located cores from within each plot. If rows of crops (cover crops or main plots) were growing, the first 7 cores were drawn from within row locations and the second 7 from interrow locations. Soil cores from each subplot were pooled and sealed in plastic lined soil sample bags. These bags were then placed under ice packs in a cooler and transported to

a refrigerated storage facility. Samples were stored in this facility at 5°C until processed. Processing took place within a month of sample collection.

Soils were processed by first gently passingthe field moist soil t hrough a 4 mm sieve. The weight of > 4mm coarse fragments was recorded to the nearest 0.1 g. The <4mm sieved soil was then placed on a 2 mm sieve. This sieve was gently shaken with a circular motion. For each soil sample, aggregates that passed through the sieve (the < 2 mm fraction) were spread out on a labeled paper plate and allowed to air dry for 3 to 5 days, then stored at room temperature (approximately 24°C) in plastic lined bags until lab analyses were performed.

Soil Analyses

Once processed, soil was analyzed for C_L as described below. Particle size analysis was performed on < 2mm sieved soil using a modified pipette method. Total C (C_T) analysis on <2mmsoil was performed with a LECO high temperature combustion analyzer (Tabatabai and Bremner, 1991). Labile soil C was estimated using the Weil et al. (2003) method, modified by reacting 2.5 ginstead of 5.0 g , of soil (<2 mm) with 20 mL of 0.02*M* $KMnO_4$ in 0.1M $CaCl_2$. The use of 2.5 g of soil was necessary because at 5 g, in soil samples having high C_L, all of the $KMnO_4$ was consumed in the reaction and accurate colorimetry was not possible. Colorimetry was performed using a single wavelength hand-held colorimeter (Hach Company, Hach Company, Loveland, CO).

Statistics

Analyses of variance on crop yields were performed using a split plot model in SYSTAT version 10 (SYSTAT Software Inc., Point Richmond, CA). Prior to final analysis of the data ANOVA assumptions were tested in SAS version 8 (SAS Institute Inc., Cary, NC). The whole-plots consisted of fields of contrasting MH. Subplots consisted of cover crop treatment. Analyses of variance performed on crop yields within a single site used the error term and degrees of freedom associated with (BLOCKS(MH)) to test whole-plot (field MH) effects. To test effects in subplots (cover crop treatment and interaction between cover crop treatment and MH) the correct error term and degrees of freedom used were those associated with the interaction COVER*(BLOCKS(MH). Inferences on effects seen at the site level should not be made beyond that site because at the site level the replication occurs as (BLOCKS(MH)). These blocks are not true replicates because the four blocks within each MH are not statistically independent. Each block is a pair of observations (one $COVER_{rye}$ and one $COVER_{bare}$) within the same experimental unit (a field of a specific MH). Thus, per Hurlbert (1984), these blocks are pseudoreplicates at the individual site level. True replication in this experiment occurs when data is analyzed across all sites.

In ANOVAs performed across all sites, each site represents a true, independent replication. When data are analyzed across all sites, the error terms described above are used, except that (BLOCKS(MH)) is replaced by (BLOCKS(MH(SITE))) because the specific MHs are unique to each site. Since each site is a replication, crop differnces among sites are accounted for by SITE in the statistical model.

Of particular interest in this research is the interaction COVER*MH. Significant interaction could be an indication that crops are responding differently to COVER in fields differing in MH. Inferences on the subplot effect of COVER should not be made because of the pseudoreplicated nature of COVER at the individual site level.

Analysis of variance on response variables across all sites was performed using a randomized complete block design where each rep (SITE) is also a block and the dependent response variable was tested against the independent variable of (MH(SITE)). Since specific details of field MH (while generally similar across all sites) are unique to each site, it is most appropriate to use (MH(SITE)) for these analyses. When using tis term, overall response means for MH can not be generated, however the overall significance of the aggregate effect of (MH(SITE)) can be tested across all sites. Again because of the pseudoreplication of (BLOCKS(MH)) at the individual site level, conclusions drawn at the individual site level should not be inferred beyond that site. Response variables at each individual site were tested against field MH.

Analysis of variance on C_T, $C_{T/Fines}$, C_L, and $C_{L/Fines}$ were analyzed using a split plot model similar to that described above for crop yields. Since soil sampling was performed before significant growth of cover crops, COVER effects and COVER*MH interactions were not considered, however since each COVER subplot within (BLOCKS(MH)) was sampled for C_T and C_L, each subplot was left in the model as an observation within (BLOCKS(MH)). The correct error term and degrees of freedom for testing the main effect MH in this model are those that are associated with (BLOCKS(MH)).

Correlation analyses were performed in SYSTAT version 10 (Systat Software Inc., Point Richmond, CA). These analyses were used to examine relationships of crop responses and yield parameters with soil C parameters.

RESULTS AND DISCUSSION

Evaluation of Holtwood Site for Systematic Effects

At Holtwood, aside from expected differences in variables between the MH_{crop} field and the MH_{sod} field, examination of dependent soil and plant variables plotted against a transect across all subplots (which systematically followed a spatial gradient) revealed no systematic trends. That is, variables exhibited only random variation across the plots within each field (Thesis Appendix C).

Cover Crop and Weed Biomass and Organic Input Estimates

Rye above- and belowground biomass means for $COVER_{rye}$ plots in each field at each site are given in Table 2.5. With the exception of rye grown at Keedysville in 2002, rye inputs were not significantly different between fields of contrasting MH at each site. At Keedysville in 2002 there was significantly more rye aboveground biomass in the MH_{crop} field. This is likely due to the P deficiency noted in the MH_{sod} field at this site in 2002. Despite P application on 30 April 2002 at Keedysville the fertilizer did not facilitate enough growth by 16 May 2002 for the rye biomass in the MH_{sod} field to catch up with that in the MH_{crop} field . Rye in the MH_{sod} field at Keedysville was also subject to grazing by deer. Any significant interactions and responses to COVER at Keedysville

in 2002 should therefore be considered in light of these unintended rye biomass differences.

Carbon inputs due to weeds on $COVER_{bare}$ plots were negligible (Table 2. 5). Greatest weed biomass occurred in the MH_{sod} field at Holtwood in 2002 where weed biomass on $COVER_{bare}$ plots was 4% of the rye biomass in $COVER_{rye}$ plots. If one assumes that typical plant material consists of 42% C (Brady and Weil, 2002) the C left on the soil in weed biomass was approximately 40 kg ha^{-1} $COVER_{bare}$ plots compared to 985 kg ha^{-1} in $COVER_{rye}$ plots in this field. The weed biomass at Holtwood in 2002 was significantly different between contrasting fields but this difference is negligible when compared to the difference between $COVER_{rye}$ and $COVER_{bare}$.

Crop Stover, Grain, and Total Biomass Yields

No significant COVER*MH interactions were seen in stover yield at any individual site in 2002 (Table 2.6). The significant difference in stover yields between MH seen at Beltsville in 2002 (Table 2.6) is likely due to the fact that the Galestown/Evesboro soils are very sandy. In 2002, Maryland experienced severe drought conditions (Figure 2.2) and the higher total SOC levels in the MH_{sod} field may have allowed for enough additional water holding capacity to generate the difference in stover between fields.

Soybean stover was significantly greater in the MH_{crop} field at Holtwood in 2002 (Table 2.6), possibly due to a difference in K availability. Soil test K in the MH_{crop} field was optimum to excessive while in the MH_{sod} field soil test K was in the moderate to optimum index range (Table 2.1). No K fertilizer was applied at this site. Soybeans have

a high K demand (Cox and Uribe, 1992) and most K taken up moves to roots by diffusion gradient, a process thatcan be i mpeded by dry soil conditions (Haby et al., 1990). The drought conditions in 2002 may have exacerbated the soil K differences in these fields, however no K analysis of soybean tissue was attempted.

In 2002 corn grain yield was significantly greater in the MH_{crop} fields at Keedysville and Upper Marlboro (Table 2.7). The MH_{sod} fields at these sites were brought directly from sod into no-till management. The sod had been killed in place with residues left in and on the soil, possibly causing N immobilization that limited grain production. Sharf et al. (2000) reported this phenomenon in corn that was grown immediately following sod in land that had been enrolled in the Conservation Reserve Program. No significant COVER*MH interactions were observed (Table 2.7).

At Beltsville in 2003, soybean stover and grain yields were significantly greater in the MH_{sod} field than in the MH_{crop} field (Table 2.6 and Table 2.7). Despite the relatively wet conditions in 2003 (Figure 2.2), C_T may again have played a role in improved water holding capacity in the MH_{sod} field at thissandy site. At Keedysville soybean stover and grain yields were significantly greater in the MH_{crop} field (Table 2.6 and Table 2.7), possibly because of the proximity of the MH_{sod} field to a forested areathat promoted crop damage by deer, according to the farm manager's experience and crop injury observations in this field. On 30 July 2003, crop injury due to deer grazing was observed to be more severe in the MH_{sod} field than in the MH_{crop} field, which was further from the tree line. While electric deer fencing was installed by the farm manager at this site in mid-July, the damage that had been incurred to that point may have been enough to cause the difference seen in crop yield parameters.

Whole plant biomass was significantly higher (29%) in MH_{crop} fields at Holtwood in 2002 and at Keedysville (56%) and Holtwood (8%) in 2003 (Table 2.8). Biomass was significantly higher (44%) in the MH_{sod} field at Beltsville in 2003. No COVER*MH interactions were seen at individual sites in 2002 but in 2003 there was significant COVER*MH interaction at Keedysville. Biomass was 27% higher in $COVER_{rye}$ in the MH_{crop} field at Keedysville compared 10% higher in $COVER_{rye}$ in the MH_{sod} field.

There were significant COVER*MH interactions in 2003 crop stover yields at Keedysville and Holtwood (Table 2.7). At Keedysville, soybean stover yield was 28% higher in $COVER_{rye}$ plots in the MH_{crop} field while in the MH_{sod} field the increase was only 11%. At Holtwood a similar trend was observed, with $COVER_{rye}$ plots in the MH_{crop} 23% more corn stover, while $COVER_{rye}$ plots in the MH_{sod} field yielded 9% less corn stover than $COVER_{bare}$ plots. A similar non-significant trend was also seen at Beltsville. The Keedysville results could possibly be confounded by deer activity but the general trend is consistent with that seen at other sites.

Grain yields at Keedysville also showed significant COVER*MH interaction in 2003, with the$COVER_{rye}$ plots yielding +27% in the MH_{crop} field, but only +7% in the MH_{sod} field (Table 2.7). If the significant interactions seen in 2003 at Keedysville and Holtwood are related to soil C changes occurring with rye treatment, it is interesting to note that these two sites are Piedmont province sites that have much higher soil fine particle contents than the sandy Coastal Plain sediments found at Upper Marlboro and Beltsville (Table 2.1). Due to the greater levels of fine particles, particularly clay, one would expect the Piedmont province soils to accumulate SOC at a faster rate than the

Coastal Plain soils (Kortleven,1963 and Jenkinson,1988b) and their level of C saturation (Six et al., 2002) would also be lower.

The overall effect of (MH(SITE)) on stover was significant in 2002 and 2003 (Table 2.6) however this effect is difficult to interpret because of the nested nature of the variables and because the general trend was not the same at each site where a significant effect was seen in analysis of the individual site. Beltsville had higher stover production in the MH_{sod} field in both 2002 and 2003 field while Holtwood and Keedysville had significantly higher stover production in their MH_{crop} fields in 2002 and 2003, respectively (Table 2.6).

The overall effect of (MH(SITE)) on grain was significant in 2003 but not in 2002. In 2003, similar to the situation described for stover, the results are difficult to interpret. No uniform trend was seen across all sites as Beltsville had a significantly higher grain yield in the MH_{sod} field while Keedysville had significanly higher grain production in the MH_{crop} field in 2003.

Overall, the effect of (MH(SITE)) on total biomass was significant in both 2002 and 2003. Again this result is diffucult to interpret for the same reasons and trends discussed for grain and stover.

No significant COVER*(MH(SITE)) interaction was seen in either grain or stover yields analyzed across all sites in 2002. In 2003 significant COVER*(MH(SITE)) interaction was present in overall stover yields but not overall grain yields across all sites (Table 2.6 and Table 2.7, respectively). In MH_{crop} fields, stover was generally higher in $COVER_{rye}$ plots than in $COVER_{bare}$ plots. In MH_{sod} fields this difference was only 2.8%.

In 2003 there was a significant overall COVER*(MH(SITE)) interaction observed in total biomass. Total biomass followed the same general trend as described for stover in 2003.

The significant interactions seen in 2003 and the yield trends observed indicated that crops were responding differently to COVER in fields of contrasting MH. Since this trend was also apparent, although not significant in 2002 the data may indicate that any beneficial effects of cover crops are cumulative in nature. This trend was similar in 3 out of 4 sites with only Upper Marlboro (2002 data) not showing signs of the general trend.

Main Crop Grain and Stover Response to Cover Crop Treatment in Fields of Contrasting Management History

Cash crop responses to COVER at each individual site are given in Table 2.9. The general trend described in the discussion in the previous section of the COVER*MH interaction is evident in the calculated responses at each site. At the individual site level the only response means that were significantly different between MH were those for stover response (R_S), grain response (R_G), and biomass response (R_B) to COVER at Keedysville in 2003. At Keedysville soybean R_S, R_G and R_B to COVER were 271%, 420%, and 315% higher in the MH_{crop} field, respectively. Again this result at Keedysville was possibly counfounded by deer grazing.

When analyzed across all sites the overall effect of (MH(SITE)) on R_S, R_G, and R_B to cover crop treatment was not statistically significant in 2002. In 2003 the overall effect was significant in R_S ($\alpha = 0.05$, $P = 0.003$) and R_B ($\alpha = 0.05$, $P = 0.009$). The overall effect of (MH(SITE)) on R_G followed the same trend as R_S and R_B, however the effect was not statistically significant.

Total C and $KMnO_4$ Labile Soil C

Analysis of C_T at each site revealed highly significant differences between fields of contrasting MH at all sites (Table 2.10). MH_{sod} fields had 87%, 112%, 114%, and 80% greater C_T than MH_{crop} fields at Beltsville, Upper Marlboro, Keedysville, and Holtwood, respectively. As seen in Table 2.10, C_L measurements between fields of contrasting MH were also highly significant at each site, following the same trend seen in C_T. MH_{sod} fields had 39%, 78%, 79%, and 36% greater C_L than MH_{crop} fields at Beltsville, Upper Marlboro, Keedysville, and Holtwood, respectively. Labile soil C and C_T were strongly related to each other (Figure 2.3). Based on preliminary SOC testing (see Table 2.1) these results were expected and essential to testing the hypothesis of greater crop response in fields that test lower for C_L. Differences among means for $C_{T/Fines}$ and $C_{L/Fines}$ are also shown in Table 2.10. These calculated parameters followed the same trends as C_T and C_L, all showing significant differences between fields of contrasting MH.

Relationships between Crop Response and soil C parameters

In 2002 relative R_S ($RELR_S$) to rye treatment across all sites was not significantly correlated with C_T or C_L (Table 2.11). Overall $RELR_S$ to rye was not significantly correlated with $C_{L/Fines}$ or $C_{T/Fines}$ in 2002. Upon examination of results within physiographic regions it was observed that in the Piedmont region (Keedysville and Holtwood) $RELR_S$ was significantly related to C_L and $C_{L/Fines}$ (Table 2.11). In the Piedmont greater responses coincided with lower levels of C_L and $C_{L/Fines}$. No significant

relationships were seen in the Coastal Plain (Beltsville and Upper Marlboro). When results at each site were examined it was observed that R_S was significantly correlated to C_T at Upper Marlboro (Table 2.12) but not at the other sites. At Upper Marlboro greater R_S to rye coincided with higher C_T levels.

Overall cash crop relative R_G ($RELR_G$) and relative R_B in 2002 were not significantly correlated with C_T, $C_{L,}$ $C_{T/Fines}$ or $C_{L/Fines}$. No significant relationships were seen within physiographic regions. When examined on a site by site basis there were no significant correlations between R_G or R_B and C_L or C_T.

In 2003 Upper Marlboro was not included in the analyses because of the lack of rye treatment as a result of wet spring field conditions. $RELR_S$ and $RELR_B$ were significantly related to C_L, C_T, and $C_{T/Fines}$ when analyzed across all other sites (Table 2.11). RELRG was significantly related to CT and $C_{T/Fines}$.

Analyses of relative responses in the Piedmont revealed that all relative crop response parameters were significantly related to all soil C parameters (Table 2.11). The relationship between $RELR_B$ and C_L in the Piedmont is shown in Figure 2.4. All crop parameters showed greater response to rye treatment at lower levels of soil C parameters. The strength of relationships of crop parameters was similar in C_L, $C_{L/Fines}$, C_T and $C_{T/Fines}$. Analyses of data across Coastal Plain sites in 2003 were not conducted because Upper Marlboro data was excluded.

At Beltsville in 2003 R_S, R_G, and R_B were significantly related to C_T but not C_L. There were greater crop responses at lower levels of C_T at Beltsville (Table 2.12). At Keedysville significantly greater R_S and R_B coincided with lower levels of both C_L and C_T. There was also a similar significant relationship between R_G and C_T but not R_G and

C_L (Table 2.12). At Holtwood R_S and R_B were significantly greater at lower levels of C_L and greater R_S also coincided with lower levels of C_T. No significant relationships between R_G and soil C parameters were seen in 2003 at Holtwood.

CONCLUSIONS

This research has shown that at three sites in the Mid-Atlantic region of the eastern U.S., cash crops grown following two years of winter rye cover crops generally tended to show a greater positive response to cover crops in fields that initially test lower in C_T and C_L when compared to cash crop responses in fields that initially test higher in C_T and C_L. Greater responses were seen in fields where C_T tested between 9.4 g kg^{-1} and 16.8 g kg^{-1} and C_L tested between 374 mg kg^{-1} and 573 mg kg^{-1}. In fields where C_T tested between 17.5 g kg^{-1} and 30.3 g kg^{-1} and C_L tested between 521 mg kg^{-1} and 778 mg kg^{-1} the positive response to rye cover crop treatment was less. This positive response is seen more conclusively in the crop stover and total biomass production. Over two years of observation, the response seemed stronger in soils having higher fine particle contents. Grain response was also observed but was less conclusive over two years than stover response. This may have been due in part to the effects environmental factors on grain production. The drought in 2002, for example, may have affected pollination.

The results of this study are somewhat inconclusive as to whether or not C_L tested by oxidation with 0.02M KMnO4 is a better predictor of crop response to soil management with winter rye than C_T tested with LECO dry combustion. These results seem to indicate that C_L tested by oxidation with 0.02M $KMnO_4$ using a modified version of the method described in Weil et al. (2003) is, at the very least, nearly as predictive as

C_T of cash crop response to soil management with winter rye. It has been shown in this study and in Weil et al. (2003) that C_L tested using this method is significantly correlated with C_T. In addition, the C_L test is far more suited to practical use in the field than are current tests for C_T. Given these facts and the results of this study, the 0.02M $KMnO_4$ C_L test seems promising as a tool for SOC based evaluation of soil quality and identification of situations where improved SOC management may lead to higher soil and crop productivity. As suggested by Weil et al. (2003) this test may be a beneficial addition to the current NRCS soil quality test kit since that kit presently does not include any test for SOC. Further work on this test should attempt to evaluate the crop response predictive potential of the test over a broader range of soils, crops, SOC management practices, and regions. Additionally, in light of the fact that the strongest relationships between crop responses and soil C parameters seen in this study were at the site that had more years of winter rye cover crop treatments (Holtwood), studies that span a longer time period may be useful in evaluation of the long term, cumulative, effects of improved SOC management.

REFERENCES

Alvarez, C.R., R. Alvarez, M.S. Grigera, and R.S. Lavado. 1998b. Associations between organic matter fractions and the active soil microbial biomass. Soil Biol. and Biochem. 30:767-773.

Alvarez, R., C.R. Alvarez, and H.S. Steinbach. 2002. Association between soil organic matter and wheat yield in humid Pampa of Argentina. Comm. Soil Sci. Plant Anal. 33:749-757.

Arshad, M.A., and G.M. Coen. 1992. Characterization of soil quality: Physical and chemical criteria. Am. J. Altern. Agric. 7:25-31.

Banerjee, M.R., and S.J. Chapman. 1996. The significance of microbial biomass sulphur in soil. Biol. Fert. Soils 22:116-125.

Bauer, A., and A.L. Black. 1994. Quantification of the effect of soil organic matter content on soil productivity. Soil Sci. Soc. Am. J. 58:185-193.

Bauer, P.J., and W.J. Busscher, 1996. Winter cover and tillage influences on Coastal Plain cotton production. J. Product. Agric. 9:50-54.

Bell, M.J., P.W. Moody, S.A. Yo, and R.D. Connoly. 1999. Using active fractions of soil organic matter as indicators of the sustainability of Ferrosol farming systems. Aust. J. Soil Res. 37:279-287.

Biederbeck, V.O., H.H. Janzen, C.A. Campbell, R.P. Zentner. 1994. Labile soil organic matter as influenced by cropping practices in an arid environment. Soil Biol. Biochem. 26:1647-1656

Blevins, R.L., W.W. Frye, and M.S. Smith. 1985. The effects of conservation tillage on soil properties. p. 99-110. In F.M. D'Itri (ed.) A systems approach to conservation tillage. Lewis Publishers, Chelsea, MI.

Blevins, R.L., J.H. Herbeck, and W.W. Frye. 1990. Legume cover crops as a nitrogen source for no-till corn and grain sorghum. Agron. J. 82:769-772.

Blair, G.J., R.D.B. Lefroy, and L. Lisle. 1995. Soil carbon fractions based on their degree of oxidation and the development of a carbon management index for agricultural systems. Aust. J. Agric. Res. 46:1459-1466.

Bowman, R.A., and R.L. Anderson. 2002. Conservation Reserve Program: effects on soil organic carbon and preservation when converting back to cropland in northeastern Colorado. J. Soil Water Conserv. 57:121-126.

Brady, N.C., and R.R. Weil. 2002. The Nature and Properties of Soils. Thirteenth edition. Prentice Hall. Upper Saddle River, New Jersey.

Bruce, R.R., G.W. Langdale, L.T. West, and W.P. Miller. 1995. Surface soil degradation and soil productivity restoration and maintenance. Soil Sci. Soc. of Am. J. 59:654-660.

Cambardella, C.A., and E.T. Elliot, 1992. Particulate soil organic matter changes across a grassland cultivation sequence. Soil Sci. Soc. Am. J. 56:777-783.

Campbell, C.A., V.O. Biederbeck, .G. McConkey, D. Curtin, and R. P. Zentner. 1999. Soil quality – Effects of tillage and fallow frequency. Soil organic matter quality as influenced by tillage and fallow frequency in a silt lom in southwester Saskatchewan. Soil Biol. Biochem. 31:1-7.

Carter, M.R, S.S. Andrews, and L.E. Drinkwater. 2004. Systems approaches for improving soil quality. p. 261-281. *In* P. Schjonning, S. Elmholt, and B.T. Christensen (ed.) Managing Soil Quality: Challenges in modern agiculture. CABI Publishing, Oxon, United Kingdom.

Cox, F.R., and E. Uribe. 1992. Potassium in two humid tropical Ultisols under a corn and soybean cropping system. I. Management. Agron. J. 84:480-484.

Custer, B.H. 1985. Soil Survey, Lancaster County, Pennsylvania. United States. Soil Conservation Service. Washington, D.C.

DeLuca, T.H., and D.R. Keeney. 1994. Soluble carbon and nitrogen pools of prairie and cultivated soils: Seasonal variation. Soil Sci. Soc. Am. J. 58:835-840.

Díaz-Zorita, M., D.E. Buschiazzo, and N. Peinemann. 1999. Soil organic matter and wheat productivity in the semiarid Argentine Pampas. Agron. J. 91:276-279.

Dick, R.P. 1992. A review: long-term effects of agricultural systems on soil biochemical and microbial parameters. Agric. Ecosys. Environ. 40:25-36.

Dick, W.A. 1983. Organic carbon, nitrogen, and phosphorus concentrations and pH in soil profiles as affected by tillage intensity. Soil Sci Soc, Am. J. 47:102-107.

Dick, W.A., E.L. McCoy, W.M. Edwards, and R. Lal. 1991. Continuous application of no-tillage to Ohio soils. Agron J. 83:65-73.

Dick, W.A., and E.G. Gregorich. 2004. Developing and maintaining soil organic matter levels. p. 103-120. *In* P. Schjonning, S. Elmholt, and B.T. Christensen (ed.) Managing Soil Quality: Challenges in modern agiculture. CABI Publishing, Oxon, United Kingdom.

Eckert, D.J. 1988. Rye cover crops for no-tillage corn and soybean production. J. Prod. Agric. 1:207-210.

Ellert, B.H. and J.R. Bettany. 1990. Calculation of organic matter and nutrients stored in soils under contrasting management regimes. Can. J. Soil Sci. 75:529-538.

Gregorich, E.G., M.R. Carter, D.A. Angers, C.M. Monreal, and B.H. Ellert. 1994. Towards a minimum data set to assess soil organic matter quality in agricultural soils. Can. J. Soil Sci. 74:367-385.

Greer, K.J. and J.J. Schoenau. 1997. Toward a framework for soil quality assessment and prediction. p. 313-321. *In* E.G. Gregorich and M.R. Carter (ed.) Soil quality for crop production and ecosystem health. Elsevier Science Publishers B.V., Amsterdam, The Netherlands.

Gruver, J.B. 1999. Relationships between farmer perceptions of soil quality and management sensitive soil parameters. M.S. Thesis. University of Maryland, Colllege Park, MD.

Gunapala, N., and K.M. Scow. 1998. Dynamics of soil microbial biomass and activity in conventional and organic farming systems. Soil Biol. Biochem. 30:805-816.

Haby, V.A., M.P. Russelle, and E.O. Skogley. 1990. Testing soils for potassium calcium and magnesium. p. 181-227 *In* R.L. Westerman (ed.) Soil testing and plant analysis. 3rd edition. Soil Science Society of America, Madison, WI.

Hagerstown Weather Station. 2001. Past Weather Data & Graphs [Online]. Available at http://i4weather.net/ (Accessed 30 June 2004; verified 1 Aug. 2004). Hagerstown Weather Station, Hagerstown, MD.

Hagerstown Weather Station. 2002. Past Weather Data & Graphs [Online]. Available at http://i4weather.net/ (Accessed 30 June 2004; verified 1 Aug. 2004). Hagerstown Weather Station, Hagerstown, MD.

Hagerstown Weather Station. 2003. Past Weather Data & Graphs [Online]. Available at http://i4weather.net/ (Accessed 30 June 2004; verified 1 Aug. 2004). Hagerstown Weather Station, Hagerstown, MD.

Hermawan, B., and A.A. Bomke. 1997. Effects of winter cover crops and successive spring tillage on soil aggregation. Soil Tillage Res. 44:109-120.

Hurlbert, S.H. 1984. Pesudoreplication and the design of ecological field experiments. Ecol. Monogr. 54:187-211.

Hu, S., N.J. Grunwald, A.H.C. van Bruggen, G.R. Gamble, L.E. Drinkwater, C Shennan, and M.W. Demment. 1997. Short-term effects of cover crop incorporation on soil carbon pools and nitrgen availability. Soil Sci. Soc. Am. J. 61:901-911.

Islam, K.R. and R.R. Weil. 2000. Soil quality indicator properties in mid-Atlantic soils as influenced by conservation management. J. Soil Water Conserv. 55:69-78.

Jenkinson, D.S., and J.N. Ladd. 1981. Microbial biomass in soil: Measurement and turnover. p. 415-471. *In* E.A. Paul and J.N. Ladd (ed.) Soil Biochemistry. Vol. 5. Marcel Dekker, New York.

Jenkinson, D.S. 1988a. Determination of microbial biomass carbon and nitrogen in soil. p. 368-386. *In* J.R. Wilson (ed.) Advances in nitrogen cycling in agricultural ecosystems. CABI Publishing, Oxon, England

Jenkinson, D.S. 1988b. Soil organic matter and its dynamics. p. 564-607. *In* A. Wild (ed.) Russell's soil conditions and plant growth. 11th ed. Longman, New York.

Kabir, Z. and R.T. Koide. 2002. Effect of autumn and winter mycorerhizal cover crops on soil properties, nutrient uptake and yield of sweet corn in Pensylvania, USA. Plant Soil 238:205-215.

Kennedy, A.C., and R.I. Papendick. 1995. Microbial characteristics of soil quality. J. Soil Water Conserv. 50:243-248.

Kessavalou, A., and D.T. Walters. 1997. Winter rye as a cover crop following soybean under conservation tillage. Agron. J. 89:68-74.

Kirby, R.M., E.D. Matthews, and M.A.Bailey. 1967. Soil Survey, Prince George's County, Maryland. U.S. Dept. of Agriculture, Soil Conservation Service. Washington, D.C.

Kortleven, J. 1963. Quantitative aspects of humus accumulation and decomposition. Versl. Landb. Ond. nr. 69.1 PUDOC, Wageningen (in Dutch).

Kravchenko, A.N., and D.G. Bullock. 2000. Correlation of corn and soybean grain yield with topography and soil properties. Agron. J. 92:75-83.

Kuo, S., Sainju, U.M., and E.J. Jellum. 1997. Winter cover crop efects on soil organic carbon and carbohydrate in soil. Soil Sci. Soc. Am. J. 61:145-152.

Large, E.C. 1954. Growth stages in cereals. Illustration of the Feekes scale. Plant Pathol. 3:128-129.

Larson W.E., and F.J. Pierce. 1994. The dynamics of soil quality as a measure of sustainable management. p. 37-51. *In* J.W.Doran, D.C. Coleman, D.F. Bezdicek, and B.A. Stewart (ed.) Defining soil quality for a sustainable environment. SSSA Spec. Publ. 35. SSSA, Madison, WI.

Lefroy, R.D.B, G.J. Blair, and W.M. Strong. 1993. Changes in soil organic matter as measured by organic carbon fractions and ^{13}C isotope abundance. Plant Soil 155/156:399-402.

Liebig, M.A. and J.W. Doran. 1999. Evaluation of farmers' perceptions of soil quality indicators. Am. J. Alt. Agric. 14:11-21.

Loveland, P., and J. Webb. 2003. Is there a critical level of organic matter in agricultural soils of temperate regions: A review. Soil Tillage Res. 70:1-18.

Maddonni, G.A., S. Urricariet, C.M. Ghersa, and R.S. Lavado. 1999. Assessing soil quality in the Rolling Pampa, using soil properties and maize characteristics. Agron. J. 91:280-287.

Majchrzak, R.N., K.N. Olson, G. Bollero, and E.D. Nafziger. 2001. Using soil properties to predict wheat yields on Illinois soils. Soil Sci. 166:267-280.

Marumoto, T., J.P. Anderson, and K.H. Domsch. 1982. Mineralization of nutrients from soil microbial biomass. Soil Biol. Biochem. 14:469-475.

Matthews, E.D. 1962. Soil survey, Washington County, Maryland. United States. Soil Conservation Service. U.S. Govt. Print. Off., Washington, D.C.

McCracken, D.V., S.J. Corak, M.S. Smith, W.W. Frye, and R.L.Blevins. 1989. Residual effects of nitrogen fertilization and winter cover cropping on nitrogen availability. Soil Sci. Soc. Am. J. 53:1459-1464.

Mendes, I.C., A.K. Bandick, R.P. Dick, and P.J. Bottomley. 1999. Microbial biomass and activities in soil aggregates affected by winter cover crops. Soil Sci. Soc. Am. J. 63:873-881.

Moody, P.W., S.A. Yo, and R.L. Aitken. 1997. Soil organic carbon, permanganate fractions, and the chemical properties of acidic soils. Aust. J. Soil Res. 35:1301-1308.

N'Dayegamiye, A., and T.S. Tran. 2001. Effects of green manures on soil organic matter and wheat yields and N nutrition. Can. J. Soil Sci. 81:371-382.

Ndiaye, E.L., Sandeno, J.M., McGrath, D. and R.P. Dick. 2000. Integrative biological indicators for detecting change in soil quality. Am. J. Alt. Agric. 15:26-36.

NOAA-NCDC. 2001. National Oceanic and Atmospheric Administration - National Climatic Data Center [Online]. Available at www7.ncdc.noaa.gov/SerialPublications/index.html (Accessed 30 June 2004; verified 1 Aug. 2004). National Climatic Data Center, Asheville, NC.

NOAA-NCDC. 2002. National Oceanic and Atmospheric Administration - National Climatic Data Center [Online]. Available at www7.ncdc.noaa.gov/SerialPublications/index.html (Accessed 30 June 2004; verified 1 Aug. 2004). National Climatic Data Center, Asheville, NC.

NOAA-NCDC. 2003. National Oceanic and Atmospheric Administration - National Climatic Data Center [Online]. Available at www7.ncdc.noaa.gov/SerialPublications/index.html (Accessed 30 June 2004; verified 1 Aug. 2004). National Climatic Data Center, Asheville, NC.

Northeast Coordinating Committee on Soil Testing. 1995. Recommended soil testing procedures for the Northeastern United States. 2nd edition. Northeast regional publication No.493, Agricultural Experiment Station, University of Delaware, Newark, DE.

Odland, T.E., and H.C. Knoblauch. 1938. The value of cover crops in continuous corn culture. J. Am. Soc. Agron. 30:22-29.

Potter, K.N., H.A. Tolbert, O.R. Jones, J.E. Matocha, J.E. Morrison, and P.W. Unger. 1998. Distributionan amount of soil organic C in long-term management systems in Texas. Soil Tillage Res. 47:309-321.

Raimbault, B.A., T.J. Vyn, and M. Tollenaar. 1990. Corn Response to rye cover crop management and spring tillage systems. Agron. J. 82:1088-1093.

Sainju, U.M., B.P. Singh, and W.F. Whitehead. 2000. Cover crops and nitrogen fertilization effects on soil carbon and nitrogen and tomato yield. Can. J. Soil Sci. 80:523-532.

Sainju, U.M., B.P. Singh, and W.F. Whitehead. 2001. Comparison of the effects of cover crops and nitrogen fertilization on tomato yield, root growth and soil properties. Scientia Horticulturae 91:2001-214.

Salinas-Garcia, J.R., F.M. Hons, and J.E. Matocha. 1997. Long-term effects of tillage and fertilization on soil organic matter dynamics. Soil Sci. Soc. Am. J. 61:152-159.

Saviozzi, A., A. Biasci, R. Riffaldi, and R. Levi-Minzi. 1999. Long-term effects of farmyard manure and sewage sludge on some soil biochemical characteristics. Biol. Fert. Soil. 30:100-106.

Scharf, P.C. ; Quarles, D.B. ; Lory, J.A. 2000. Nitrogen response of no-till corn in first and second years following Conservation Reserve Program. Comm. soil sci. plant anal. 31:2501-2508.

Shang, C., and H. Tiessen. 1997. Organic matter lability in tropical Oxisol: Evidence from shifting cultivation, chemical oxidation, particle size, and magnetic fractionations. Soil Sci. 162:795-807.

Sikora, L.J., and D.E. Stott. 1996. Soil Organic Carbon and Nitrogen. p. 157-167. *In* J.W.Doran and A.J. Jones (ed.) Methods for assessing soil quality. SSSA Spec. Publ. 35. SSSA, Madison, WI.

Six, J., R.T. Conant, E.A. Paul, and K. Paustian. 2002. Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. Plant Soil 241:155-176.

Smith, M.S., W.W. Frye, and J.J. Varco. 1987. Legume winter cover crops. Adv Soil Sci. 7:95-139.

Stine, M.A., and R.R. Weil. 2002. The relationship between soil quality and crop productivity across three tillagesystems in south central Honduras. Am. J. Altern. Agric. 17:2-8.

Strickling, E. 1975. Crop sequences and tillage in efficient crop production. p. 20-29 *In* Agron. Abstr. American Society of Agronomy, Madison, WI.

Tabatabai, M.A., and J.M. Bremner. 1991. Automated instruments for determination of total carbon, nitrogen, and sulfur in soils by combustion techniques. p. 261-286. *In* K.A. Smith (ed.) Soil analysis: Modern instrumental techniques. 2nd ed. Dekker, New York.

Tiessen, H., E. Cuevas, and P. Chacon. 1994. The role of soil organic matter in sustaining soil fertility. Nature 371:783-785.

Tirol-Padre, A., and J.K. Ladha. 2004. Assessing the reliability of permanganate-oxidizable carbon as an index of soil labile carbon. Soil Sci. Soc. Am. J. 68:969-978.

Tisdall, J.M., and J.M. Oades. 1982. Organic matter and water stable aggregates in soils. J. Soil Sci. 33:141-163.

Torbert, H.A., D.W. Reeves, and R.L. Mulvaney. Winter legume cover crop benefits to corn: rotation vs. fixed-nitrogen effects. Agron J. 88:527-535.

USDA-NRCS. 2003. The soil quality test kit guide [Online]. Available at http://soils.usda.gov/sqi/soil_quality/assessment/kit2.html (Accessed 1 Oct. 2004; verified 25 Nov. 2004). Natural Resources Conservation Service and Agricultural Research Service, US Dept. of Agriculture, Lincoln, NE and Washington, DC.

Utomo, M., W.W. Frye, and R.L. Blevins. 1990. Sustaining soil nitrogen for corn using hairy vetch cover crop. Agron. J. 82:979-983.

Vaughan, J.D. and G.K. Evanylo, 1998. Corn response to cover crop species, spring desiccation time, and residue management. Agron. J. 90:536-544.

Wagger, M.G., M.L. Cabrera, and N.N. Ranells. 1998. Nitrogen and carbon cycling in relation to cover crop residue quality. J. Soil Water Conserv. 53:214-218.

Wander, M.M., S.J. Traina, B.R.Stinner, an S.E. Peters. 1994. Organic and conventional management effects on biologically active soil organic matter pools. Soil Sci. Soc. Am. J. 8:1130-1139.

Wander, M.M., and G.A. Bollero. 1999. Soil quality assessment of tillage impacts in Illinois. Soil Sci. Soc. Am. J. 63:961-971.

Wander, M.M., and M.G. Bidart. 2000. Tillage practice influences on the physical protection, bioavailability and composition of particulate organic matter. Biol. Fertil. Soils 32:360-367.

Wander, M.M., and L.E. Drinkwater. 2000. Fostering soil stewardship through soil quality assessment. Appl. Soil Ecol. 15:61-73.

Weil, R.R. 1992. Inside the heart of sustainable farming: an intimate look at soil life--and how to keep it thriving. The New Farm 14:48, 43, 45.

Weil, R.R., K.R. Islam, M.A. Stine, J.B. Gruver, and S.E. Samson-Liebig. 2003. Estimating active carbon for soil quality assessment: A simplified method for lab and field use. Am. J. Altern. Agric. 18:3-17.

Weil, R.R., and F. Magdoff. 2004. Significance of soil organic matter to soil quality and health. p. 1-43. *In* F. Magdoff and R.R. Weil (ed.) Soil organic matter in sustainable agriculture. CRC Press. Boca Raton, FL.

FIGURES AND TABLES

Table 2.1. Management history, soil series classification, taxonomic classification, initial pH, preliminary C_T (loss on ignition), and A horizon particle size analysis (by micropipette method) of the soils found contrastingly managed fields at four research sites.

Site	FMH†	Soil Series and A horizon texture	Taxonomic Class	pH§	C_T§	P Index¶	K Index¶	Clay	Silt	Sand
					g kg^{-1}			g kg^{-1}	g kg^{-1}	g kg^{-1}
Beltsville	Cropped	Evesboro / Galestown sand / loamy sand	Mesic, coated Typic Quartzipsamments / Siliceous, mesic Psammentic Hapludults.	6.3	20.0	150.0 E	52.0 O	163	111	726
Beltsville	Sod	Evesboro / Galestown sand / loamy sand	Mesic, coated Typic Quartzipsamments / Siliceous, mesic Psammentic Hapludults.	6.0	32.4	127.9 E	55.9 O	196	90	714
Upper Marlboro	Cropped	Adelphia / Donlonton fine sandy loam	Fine-loamy, mixed, active, mesic Aquic Hapludults / Fine-loamy, glauconitic, mesic Aquic Hapludults.	5.9	23.0	29.4 M	64.6 O	324	195	481
Upper Marlboro	Sod	Adelphia / Donlonton fine sandy loam	Fine-loamy, mixed, active, mesic Aquic Hapludults / Fine-loamy, glauconitic, mesic Aquic Hapludults.	5.2	51.0	33.0 M	70.6 O	333	182	485
Keedysville	Cropped	Hagerstown silt loam	Fine, mixed, semiactive, mesic Typic Hapludalfs.	6.5	36.0	141.4 E	141.0 E	255	597	148
Keedysville	Sod	Hagerstown silt loam	Fine, mixed, semiactive, mesic Typic Hapludalfs.	6.2	62.3	21.8 L	133.1 E	254	570	176
Holtwood	Cropped	Glenelg / Chester channery loam / silt loam	Fine-loamy, mixed, semiactive, mesic Typic Hapludults.‡	6.7	38.0	426.9 E	109.6 E	319	477	204
Holtwood	Sod	Glenelg / Chester channery loam / silt loam	Fine-loamy, mixed, semiactive, mesic Typic Hapludults.‡	6.8	58.0	194.6 E	60.5 O	362	556	82

† FMH: Field management history determined through farmer interviews and research of farm records.

‡ Chester soils and Glenelg soils both fall into this taxonomic class.

§ Values were measured in the A horizon (0-15cm depth) before any experimental treatments were applied.

¶ Nutrient index ratings: Low (L): 0 – 25; Medium (M): 26 – 50; Optimum (O): 51 – 100; Excessive (E): 100+.

Table 2.2. Range of characteristics observed in the soil profiles of fields having similar soils but contrasting management histories at four research sites.

Horizon	Cropped Management History†		Sod Management History†	
	Depth ‡	Soil Description§	Depth ‡	Soil Description§
		Beltsville		
	cm		cm	
Ap	0 to 15-20	10YR3/3 to 10YR5/3, loamy sand	0 to 15-25	10YR3/4 to 10YR4/6, loamy sand
AB¶	25 to 35	10YR5/6, loamy sand	25 to 35-45	10YR5/6, loamy sand
Bw / Bt	25-35 to 55-85	10YR6/3 to 10YR7/6, loamy sand to sandy clay loam, weak redox., common ironstone.	25-45 to 65-85	10YR6/6 to 10YR6/8, loamy sand to sandy clay loam, common ironstone
C	55-85 ...	10YR5/8 to 10YR8/2, sand to clay loam, weak redox., few ironstone.	65-85 ...	10YR4/4 to 10YR7/8, sand to sandy loam
		Upper Marlboro		
Ap	0 to 20-25	2.5YR4/4 to 2.5YR5/4, 10YR3/3, fine sandy loam	0 to 15-25	2.5Y4/4, 10YR3/4 to 10YR4/4, fine sandy loam, weak redox.
AB¶	20 to 35	2.5YR5/4, fine sandy loam, weak redox.	15 to 25-35	2.5Y5/4, 10YR3/4 to 10YR5/4, fine sandy loam, weak redox.
Bt	25-35 to 55-85	5G5/1, 2.5YR5/4, 10YR4/4 to 10YR5/4, fine sandy loam to fine sandy clay loam, moderate redox.	25-35 to 55-90	5G5/1, 2.5Y5/4, 10YR3/6 to 10YR5/6, fine sandy loam to fine sandy clay loam, moderate redox.
C	55-85 ...	5G5/1, 2.5YR5/4, 7.5YR5/8, fine sandy loam	55-90 ...	5G5/1, 2.5Y5/4, 7.5YR5/8, fine loamy sand to fine sandy loam, strong redox.
		Keedysville		
Ap	0 to 15	7.5YR3/4, silt loam	0 to 10-25	7.5YR4/6, silt loam
BE	15 to 25-65	7.5YR4/6 to 7.5YR6/8, silt loam	10-25 to 25-45	7.5YR4/6 to 7.5YR5/8, silt loam
Bt	25-65 ...	7.5YR4/6 to 7.5YR6/8, 5YR5/8, silt loam to silty clay loam, weak redox.	25-45 ...	7.5YR5/6 to 7.5YR5/8, 5YR5/8, silt loam to silty clay loam, weak redox.
		Holtwood		
Ap	0 to 25	10YR3/6, silt loam	0 to 30	10YR3/4, silt loam
AB	25 to 35-45	7.5YR5/8 to 10YR4/6, silt loam	30 to 45-55	7.5YR5/8 to 10YR4/4, silt loam
Bt1	35-45 to 55-75	7.5YR5/8, silt loam	45-55 to 55-65	7.5YR5/8, silt loam, moderate amounts of shist fragments
Bt2	55-75 ...	5YR5/8 to 7.5YR5/8, silty clay loam, weak redox, moderate amounts of shist fragments	55-65 ...	5YR5/8 to 7.5YR5/8, silty clay loam, weak redox, moderate amounts of shist fragments

† Field management history was determined through farmer interviews and research of farm records.

‡ Depths given are ranges that reflect the lowest to highest depths seen for the upper and lower horizon boundary.

§ Soil description includes Munsell soil color range, soil texture (by feel) range, redoximorphic features (redox.), other features.

¶ Horizon not present in all auger borings along transect.

Figure 2.1. Typical experimental field layout used at Beltsville, Keedysville, and Upper Marlboro.

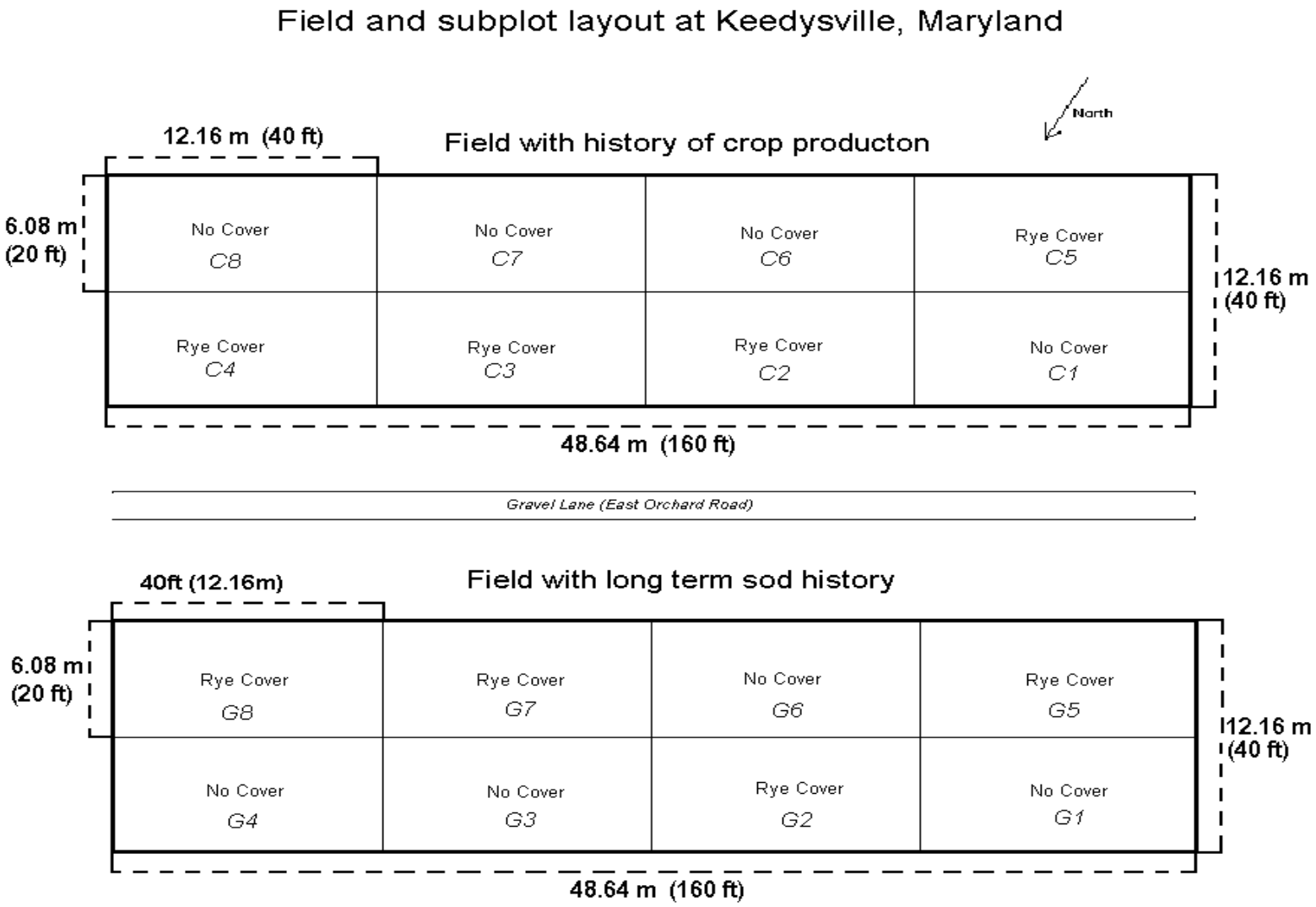


Table 2.3. Field management histories at four research sites.

Site	Field Management History†	
	Cropped	Sod
Beltsville	The field had been in continuous crop production, including periods in which conventional tillage‡ was used, since at least 1967. Exact timings of tillage practices are not known. The last tilling of this field was in 1999 using chisel tillage. It has been in no-till production since.	The field had been under sod for at least 40 years. In the year 2000 the sod was plowed under with chisel tillage and the field was subsequently brought into no-till production.
Upper Marlboro	The field had been in continuous crop production, including periods in which conventional tillage‡ was used, since at least 1967. It was moldboard tilled in spring 1995 and spring 1996. Seedbed preparation was done with chisel tillage from 1997 until this study.	The field had been under sod since 1983. It was brought into no-till production at the beginning of this study.
Keedysville	The field was in continuous production, including conventional tillage‡, until 1949. From 1949-1982 the U.S. military owned the land and allowed it to undergo early natural succession with only occasional mowing. The field was brought into no-till production in 1982. Seedbed preparation was through conventional tillage‡ from 1991 to 1995. From 1996 on the field was under no-till cropping.	The field had been under sod since 1982 and under natural vegetation prior to that dating back to at least 1950. It was brought into no-till production at the beginning of this study.
Holtwood	The field was conventionally tilled‡ on an annual basis from at least 1967 until 1991. In 1991 it was converted to no-till agriculture.	The field had been under sod since at least 1967. From 1967 to 1990 it was used as a grazed pasture. No-till production started in 1991.

† Field management history was determined through farmer interviews and research of farm records.
‡ Conventional tillage through use of a moldboard plow.

Table 2.4. Crop production schedules at four research sites for rye winter cover crops and subsequent summer crops.

Site	Cover crop planting date	Cover crop kill date	Main crop planting date	Main crop fertilization dates, fertilizer rate, fertilizer compound	Main crop harvest date
			Winter 2001 / Summer 2002		
Beltsville	24 Oct. 2001	1 May 2002	Corn, 27 Apr. 2002	27 Apr.: 33.6 kg ha^{-1} N, ammonium nitrate†; 6 June: 106.4 kg ha^{-1} N, ammonium nitrate.	18 Sept. 2002
Upper Marlboro	26 Nov. 2001	15 May 2002	Corn, 31 May 2002	15 May: 33.6 kg ha^{-1} N, urea ammonium nitrate; 3 June: 33.6 kg ha^{-1} N, urea ammonium nitrate; 19 June: 33.6 kg ha^{-1} N, urea ammonium nitrate; 2 July: 56.0 kg ha^{-1} N, urea ammonium nitrate.	29 Sept. 2002
Keedysville	20 Nov. 2001	16 May 2002	Corn, 30 May 2002	11 Apr.: 56.0 kg ha^{-1} N, Urea; 30 May: 56.0 kg ha^{-1} P, triple super phosphate;‡ 30 May: 112.1 kg ha^{-1} N, Urea.	5 Oct. 2002
Holtwood	29 Oct. 2001	22 Apr. 2002	Soybeans, 29 Apr. 2002	None Applied	8 Oct. 2002
			Winter 2002 / Summer 2003		
Beltsville	18 Oct. 2002	12 May 2003	Soybeans, 25 June 2003	None Applied	7 Oct. 2003
Upper Marlboro	15 Nov. 2002	7 July 2003	Soybeans, 18 July 2003	None Applied	9 Oct. 2003
Keedysville	28 Oct. 2002	20 May 2003	Soybeans, 30 May 2003	44.8 kg ha^{-1} P, 56.9 kg ha^{-1} K, potassium metaphosphate.‡§	17 Oct. 2003
Holtwood	29 Oct. 2002	2 May 2003	Corn, 15 May 2003	15 May: 84.1 kg ha^{-1} N, ammonium nitrate; 17 June: 84.1 kg ha^{-1} N, ammonium nitrate.	11 Oct. 2003

† At Beltsville 16.8 kg ha^{-1} of N resulting from 2001 soybean stubble were taken into account when 2002 fertilizers were applied.

‡ Per Univ. of MD Soil Testing Laboratory recommendations, P was applied to Keedysville sod history plot only.

§ Potassium metaphosphate was the only P supplying fertilizer available at the time at the Keedysville site. Plant response to K applied should have been negligible because all plots at Keedysville tested excessive for K content.

Figure 2.2. Monthly precipitation levels and departures from normal for 2001, 2002, and 2003 at four research sites.

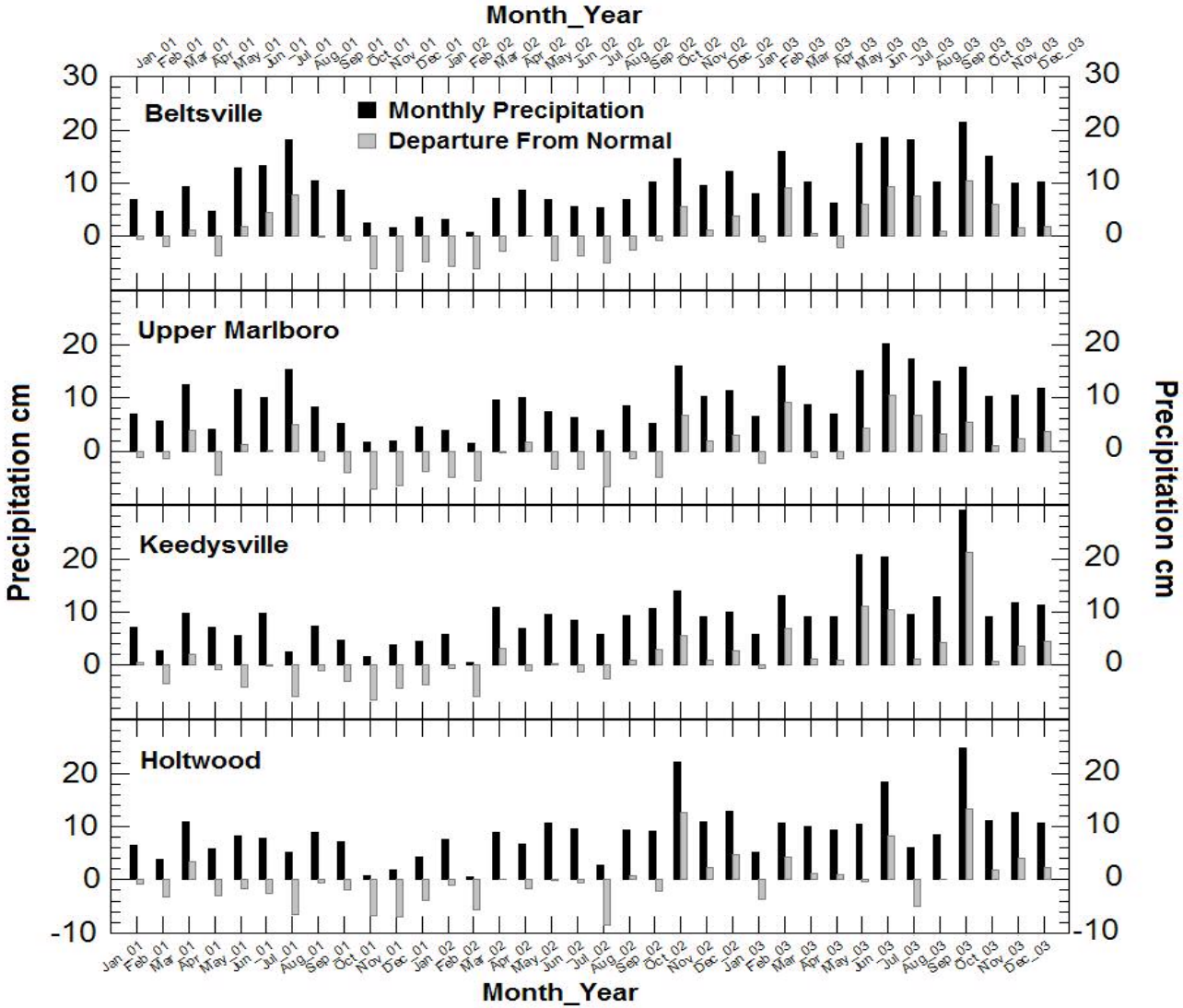


Table 2.5. Rye and weed above- (Shoots) and belowground (Roots to 0-7.5cm depth) biomass means in 2002 and 2003 for each site.

			Year					
			2002			2003		
			Field Management History			Field Management History		
Site	Cover plant	Plant part	cropped		sod	cropped		sod
			kg ha^{-1}					
Beltsville	Rye	Roots	923.3		1642.1	2125.3		2340.0
	Rye	Shoots	2845.0		3602.5	1830.0		2362.5
	Weeds	Roots	--		--	55.0		26.8
	Weeds	Shoots	--		--	47.3		111.8
Upper Marlboro	Rye	Roots	1387.6	***	7729.6	--		--
	Rye	Shoots	4212.5		3117.5	--		--
	Weeds	Roots	--		--	--		--
	Weeds	Shoots	--		--	--		--
Keedysville	Rye	Roots	2847.9		3988.9 †	630.5	*	1957.2 †
	Rye	Shoots	7537.5	*	2702.5 †	2365.0		2340.0 †
	Weeds	Roots	--		--	2.7		--
	Weeds	Shoots	25.5		78.6	3.9		7.3
Holtwood	Rye	Roots	1578.4		1175.1	760.6		650.0
	Rye	Shoots	3802.5		2345.5	637.5		630.0
	Weeds	Roots	--		--	23.9		1.2
	Weeds	Shoots	23.5	*	95.1	7.6		14.2

*,**,*** Adjacent means are significantly different from each other at $P < 0.05$, $P < 0.01$, and $P < 0.001$.

† Rye in these plots was subject to grazing by deer.

Table 2.6. Mean dry stover yields of summer crops grown in 2002 and 2003.

	Field Management History			Cover crop level within Field Management History				
				Cropped			Sod	
Site / Year	Cropped		Sod	Rye	No Rye		Rye	No Rye
2002				2002 Dry Stover kg ha^{-1}				
Beltsville	4845.5	*	6133.7	5105.3	4585.7		5737.7	6529.6
Upper Marlboro	6325.9		6023.8	6763.9	5887.8		7343.6	4704.1
Keedysville	6651.7		7153.6	8423.7	4879.6		8044.6	6262.6
Holtwood[§]	9533.2	*	7566.8	10188.3	8878.1		7868.4	7265.2
All Sites	Significance of (MH(SITE))			Significance of the interaction COVER*(MH(SITE))				
Overall effects[‡]		*			NS[§]			
2003				2003 Dry Stover kg ha^{-1}				
Beltsville	3431.6	*	4855.9	3897.9	2965.3		4791.3	4918.5
Upper Marlboro	N/A[¶]		N/A[¶]	N/A[¶]	N/A[¶]		N/A[¶]	N/A[¶]
Keedysville	5141.2	*	3284.0	5770.9	4511.6	†	3453.9	3114.4
Holtwood[§]	5689.3		5183.8	6284.2	5094.5	†	4956.7	5410.7
All Sites	Significance of (MH(SITE))			Significance of the interaction COVER*(MH(SITE))				
Overall effects[‡]		***				†		

* Adjacent means are significantly different at P<0.05.

† For site means: Indicates significant interaction between cover crop treatment and FMH at P < 0.05. For overall effects indicates significant interaction between cover crop treatments and FMH when tested across all sites.

‡ Overall effects of MH(SITE) tested across all sites and interaction between COVER and MH(SITE). Overall significance can be tested but individual means can not be generated due to nested nature of variables.

§ NS: Overall effect is not statistically significant.

¶ N/A Upper Marloboro data was excluded from 2003 analyses due to the killing of cover crops by wet spring field conditions.

Table 2.7. Mean dry grain yields of cash crops grown in 2002 and 2003.

	Field Management History			Cover crop level within Field Management History				
				Cropped			Sod	
Site / Year	Cropped		Sod	Rye	No Rye		Rye	No Rye
2002	2002 Dry Grain kg ha^{-1}							
Beltsville	6444.1		6258.5	6709.2	6179.0		7510.9	5006.2
Upper Marlboro	5482.9	*	4241.1	5439.9	5525.9		4028.2	4454.0
Keedysville	8741.8	*	7406.0	8853.4	8630.1		7660.9	7151.1
Holtwood[§]	4299.2		3193.3	4675.7	3922.8		3723.2	3113.4
All Sites	Significance of (MH(SITE))			Significance of the interaction COVER*(MH(SITE))				
Overall effects[‡]	NS[§]			NS[§]				
2003	2003 Dry Grain kg ha^{-1}							
Beltsville	1846.6	*	2722.7	2080.1	1613.0		2635.8	2809.5
Upper Marlboro	N/A[¶]		N/A[¶]	N/A[¶]	N/A[¶]		N/A[¶]	N/A[¶]
Keedysville	3179.9	*	2037.4	3555.1	2804.6	†	2109.5	1965.3
Holtwood[§]	10015.5		9369.7	10316.5	9314.4		9606.7	9132.6
All Sites	Significance of (MH(SITE))			Significance of the interaction COVER*(MH(SITE))				
Overall effects[‡]	***			NS[§]				

* Adjacent means are significantly different at P<0.05.

† For site means: Indicates significant interaction between cover crop treatment and FMH at P < 0.05. For overall effects indicates significant interaction between cover crop treatments and FMH when tested across all sites.

‡ Overall effects of MH(SITE) tested across all sites and interaction between COVER and MH(SITE). Overall significance can be tested but individual means can not be generated due to nested nature of variables.

§ NS: Overall effect is not statistically significant.

¶ N/A Upper Marloboro data was excluded from 2003 analyses due to the killing of cover crops by wet spring field conditions.

Table 2.8. Mean dry total biomass yields of summer crops grown in 2002 and 2003.

	Field Management History			Cover crop level within Field Management History				
				Cropped			Sod	
Site / Year	Cropped		Sod	Rye	No Rye		Rye	No Rye
2002	2002 Dry Biomass kg ha^{-1}							
Beltsville	11,289.6		12,392.2	11,814.5	10,764.7		13,248.6	11,535.8
Upper Marlboro	11,808.7		10,265.0	12,203.8	11,413.7		11,371.8	9158.1
Keedysville	15,393.4		14,559.5	17,277.1	13,509.7		15,705.4	13,413.7
Holtwood[§]	13,832.4	*	10,760.1	14,864.0	12,800.9		11,141.5	10,378.6
All Sites	Significance of (MH(SITE))			Significance of the interaction COVER*(MH(SITE))				
Overall effects[‡]		*			NS[§]			
2003	2003 Dry Biomass kg ha^{-1}							
Beltsville	5278.2	*	7577.6	5978.0	4578.4		7427.1	7728.0
Upper Marlboro	N/A[¶]		N/A[¶]	N/A[¶]	N/A[¶]		N/A[¶]	N/A[¶]
Keedysville	8321.1	*	5321.5	9326.0	7316.2	†	5563.4	5079.6
Holtwood[§]	15,704.8	*	14,553.4	17,000.7	14,408.9		14,563.4	14,543.4
All Sites	Significance of (MH(SITE))			Significance of the interaction COVER*(MH(SITE))				
Overall effects[‡]		***			††			

*, **, *** Adjacent means are significantly different at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively. For overall effects indicates significance of effect at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

†,†† For site means: Indicates significant interaction between cover crop treatment and FMH at $P < 0.05$ and $P < 0.01$, respectively. For overall effects indicates significant interaction between cover crop treatments and FMH when tested across all sites.

‡ Overall effects of MH(SITE) tested across all sites and interaction between COVER and MH(SITE). Overall significance can be tested but individual means can not be generated due to nested nature of variables.

§ NS: Overall effect is not statistically significant.

¶ N/A Upper Marloboro data was excluded from 2003 analyses due to the killing of cover crops by wet spring field conditions.

Table 2.9. Mean crop responses to cover crop treatment within fields of contrasting management history.

Site	Field Management History: Cropped	Field Management History: Sod	Field Management History: Cropped		Field Management History: Sod
	2002 Stover Response (kg ha^{-1})		2003 Stover Response (kg ha^{-1})		
Beltsville	519.5	-791.9	932.5		-127.1
Upper Marlboro	876.0	2639.5	N/A[¶]		N/A[¶]
Keedysville	3544.1	1782.0	1259.3	*	339.6
Holtwood[‡]	1310.2	603.2	1189.6		-454.0
Overall[§]	NS[†]		**		
	2002 Grain Response (kg ha^{-1})		2003 Grain Response (kg ha^{-1})		
Beltsville	530.2	2504.7	467.1		-173.8
Upper Marlboro	-85.9	-425.8	N/A[¶]		N/A[¶]
Keedysville	223.3	509.8	750.5	*	144.2
Holtwood[‡]	752.3	159.7	1402.2		474.1
Overall[§]	NS[†]		NS[†]		
	2002 Total Biomass Response (kg ha^{-1})		2003 Total Biomass Response (kg ha^{-1})		
Beltsville	1049.7	1712.8	1399.6		-300.9
Upper Marlboro	790.1	2213.7	N/A[¶]		N/A[¶]
Keedysville	3767.4	2291.7	2009.8	*	483.8
Holtwood[‡]	2063.1	762.9	2591.8		20.1
Overall[§]	NS[†]		**		

* Adjacent means are significantly different at $P < 0.05$.

† NS: No significant effect.

‡ Holtwood produced soybeans in 2002 and corn in 2003. All other sites produced corn in 2002 and soybeans in 2003.

§ Overall significance of the effect of MH(SITE) on crop response to rye, tested across all sites (*,** Significant effect at $P < 0.05$ and $P < 0.01$, respectively).

¶ N/A Upper Marloboro data was excluded from 2003 analyses due to the killing of cover crops by wet spring field conditions.

Table 2.10. Mean values for total C, total C / soil fine content (percent clay plus percent silt), $KMnO_4$ labile soil C, and $KMnO_4$ labile soil C / soil fine content in fields of contrasting management history at each research site.

Site	Field Management History			Field Management History		
	Cropped		Sod	Cropped		Sod
	Total C†			Labile Soil C†		
	g kg^{-1}			mg kg^{-1}		
Beltsville	9.40	***	17.57	374.16	**	520.64
Upper Marlboro	11.68	***	24.80	413.70	***	738.12
Keedysville	13.27	***	28.44	413.36	***	740.76
Holtwood	16.81	***	30.23	572.56	***	777.63
	Total C / soil fines			Labile C / soil fines‡		
	g kg^{-1}			mg kg^{-1}		
Beltsville	34.36	***	61.61	1367.64	**	1825.41
Upper Marlboro	22.48	***	48.12	796.53	***	1432.46
Keedysville	15.57	***	34.52	485.19	***	899.17
Holtwood	21.12	***	32.91	719.40	**	846.67

*, **, *** Adjacent means are significantly different at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

† Samples were taken in Oct. 2001 at Holtwood. All other sites were sampled in Jan. 2002.

Figure 2.3. The relationship between total soil C content and labile soil C content in soils across four research sites. The Guassian bivariate confidence ellipse has P=0.6278 and *** indicates correlation is significant at P < 0.001.

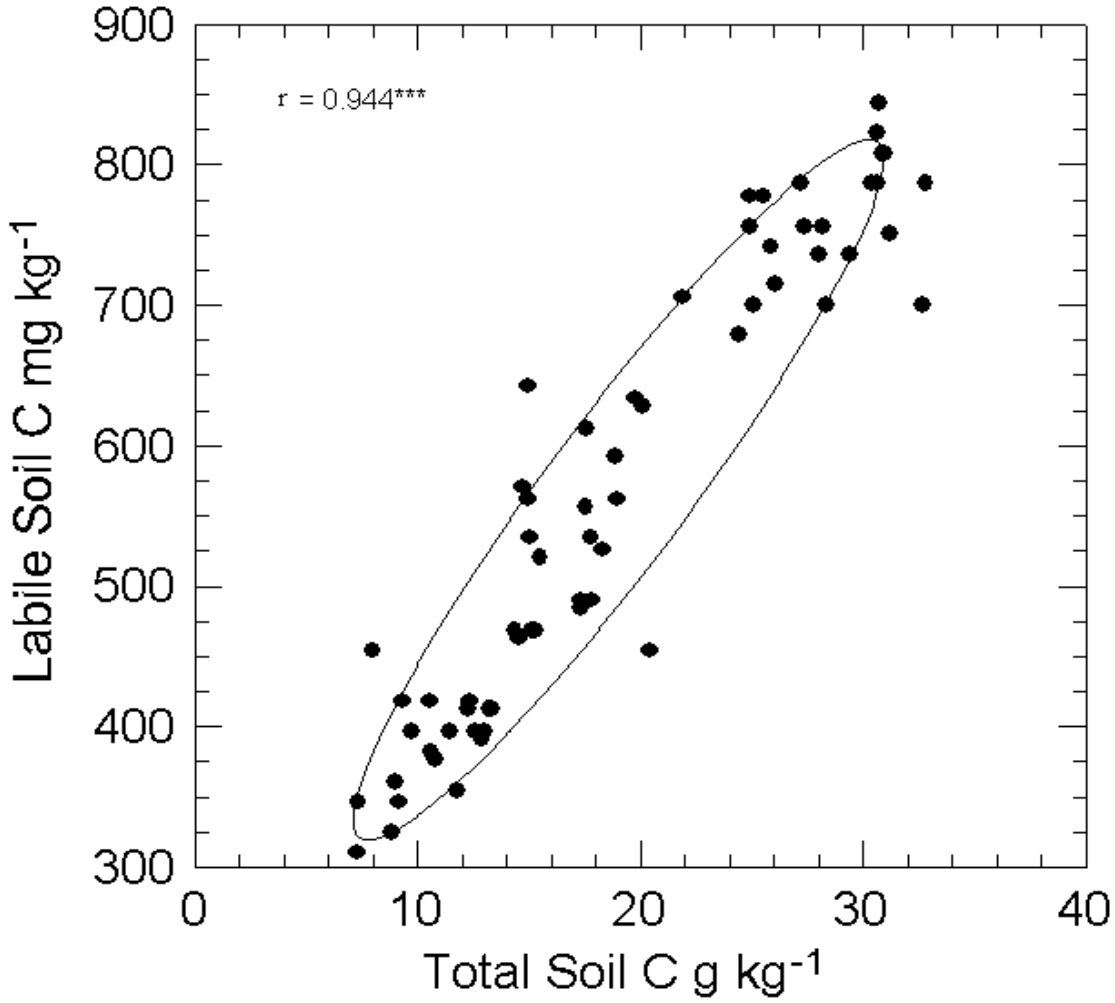


Table 2.11. Correlations between relative cash crop responses to rye cover crops and soil C parameters across all sites, within Piedmont Province sites, and within Coastal Plain sites in 2002 and 2003.

	2002			2003		
Soil C Parameter	RR_S	RR_G	RR_B	RR_S	RR_G	RR_B
	Correlation coefficient (r)					
	All Sites					
C_L	0.016	-0.161	0.000	-0.479*	-0.346	-0.419*
$C_{L/Fines}$	-0.255	0.294	0.056	-0.168	-0.196	-0.182
C_T g	0.049	-0.140	0.039	-0.568**	-0.429*	-0.503*
$C_{T/Fines}$	-0.162	0.246	0.131	-0.468*	-0.486*	-0.484*
	Piedmont Sites					
C_L	-0.599*	0.108	-0.263	-0.663**	-0.535*	-0.636**
$C_{L/Fines}$	-0.610*	0.166	-0.227	-0.553*	-0.527*	-0.576*
C_T	-0.478	0.027	-0.231	-0.680**	-0.507*	0.622**
$C_{T/Fines}$	-0.482	0.061	-0.204	-0.614*	-0.509*	-0.589*
	Coastal Plain Sites					
C_L	0.464	-0.249	0.192	N/A	N/A	N/A
$C_{L/Fines}$	-0.107	0.314	0.170	N/A	N/A	N/A
C_T	0.478	-0.177	0.280	N/A	N/A	N/A
$C_{T/Fines}$	0.060	0.247	0.287	N/A	N/A	N/A

*, ** Correlation is significant at $P < 0.05$ and $P < 0.01$, respectively.

Figure 2.4. The relationship between relative total biomass response to rye with labile soil C content in soils at two sites in the Piedmont physiographic region of the Mid-Atlantic U.S. The Guassian bivariate confidence ellipse has P=0.6278 and ** indicates correlation is significant at P < 0.01.

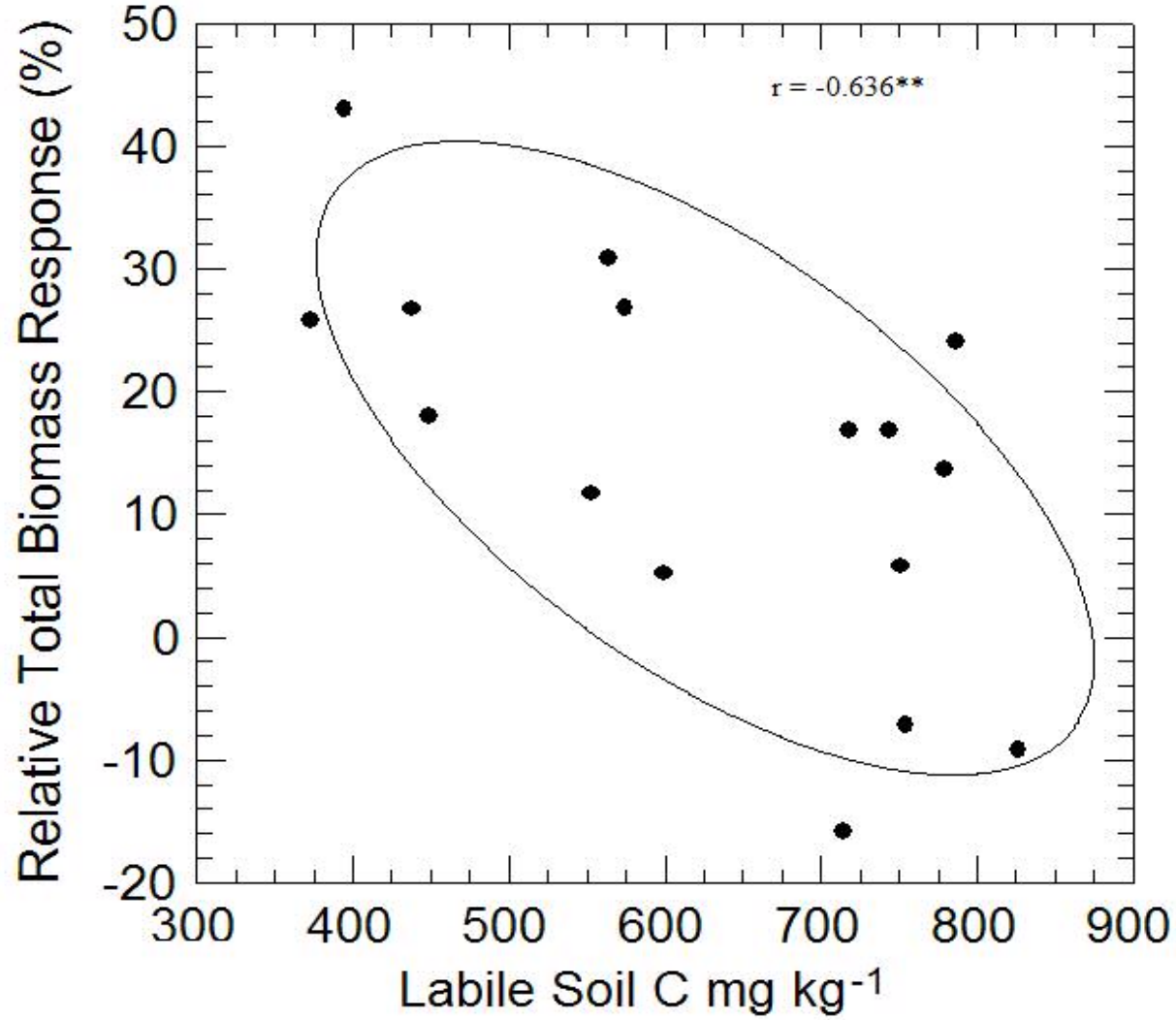


Table 2.12. Correlations between cash crop responses to rye cover crops and soil C parameters at four sites in the Mid Atlantic region of the eastern U.S.

	2002			2003		
Soil C Parameter	R_S	R_G	R_B	R_S	R_G	R_B
	Correlation coefficient (r)					
	Beltsville, MD					
C_L	-0.434	0.297	-0.126	-0.377	-0.386	-0.383
C_T	-0.196	0.462	0.148	-0.731*	-0.772*	-0.751*
	Upper Marlboro, MD					
C_L	0.702	-0.116	0.536	N/A	N/A	N/A
C_T	0.716*	-0.023	0.596	N/A	N/A	N/A
	Keedysville, MD					
C_L	-0.548	0.160	-0.280	-0.744*	-0.670	-0.716*
C_T	-0.553	0.093	-0.326	-0.787*	-0.716*	-0.760*
	Holtwood, PA					
C_L	-0.196	-0.325	-0.275	-0.837**	-0.520	-0.740*
C_T	-0.131	-0.266	-0.206	-0.770*	-0.441	-0.663

*, ** Correlation is significant at $P < 0.05$ and $P < 0.01$, respectively.

CHAPTER THREE

Labile Soil Carbon Test to Predict Soil Response to Improved Organic Matter Management. II: Soil Function Responses

INTRODUCTION

Soil organic matter (SOM) management is a key facet of maintenance or improvement of soil quality (Gregorich et al., 1994; Larson and Pierce, 1994; Islam and Weil, 2000; Wander and Drinkwater, 2000). Improved SOM management has been shown to enhance soil functions related to soil quality (Karlen et al., 1992; Seybold et al., 1996). Management practices designed to improve soil quality are best evaluated with indicators that rapidly respond to soil management (Islam and Weil, 2000). The effects of contrasting soil management practices may take years to become apparent in measurements of total soil organic C (SOC) (Sikora and Stott, 1996; Weil et al., 2003).

Soil organic C measurements related to the fraction of total SOC that is microbially labile can serve as indicators of soil quality change. Included among these labile parameters are microbial biomass C (Kenedy and Papendick, 1995; Islam and Weil, 2000), microbial biomass N (Jenkinson, 1988a), mineralizable C (C_{min}), mineralizable N (N_{min}) (Gregorich et al., 1994), microbial enzymatic activity (Dick, 1992; Ndiaye et al., 2000), particulate organic matter (Cambardella and Elliot, 1992; Wander and Bidart, 2000), light fraction organic matter (Christensen, 1992; Wander et al., 1994), soil carbohydrates measured as anthrone-reactive C (Deluca and Keeny, 1993; Saviozzi et al., 1999) and soil aggregation (Cambardella and Elliot, 1993).

The tests mentioned above are laboratory intensive methods. There is a need for simple soil quality assessment tools that can be used in the field to facilitate soil management decisions (Liebig and Doran, 1999; Wander and Drinkwater, 2000). Measurement of labile organic soil C (C_L) with potassium permanganate ($KMnO_{4)}$ may be a suitable method for inclusion in a field-testing kit. This method is described in detail in the Introduction and Materials and Methods sections in Chapter Two. A more historically oriented discussion of the development of method is given in Chapter One. The most cited version of this procedure was developed by Blair et al. (1995). Weil et al. (2003) simplified the Blair et al., (1995) method and made it practical for field use. The Weil et al. (2003) method is also more specific to labile forms of soil C rather than recalcitrant forms.

Weil et al. (2003) found their $KMnO_4$ oxidation method to bemore sensitive to tillage treatments than total SOC and more closely correlated with other soil quality indicators (microbial biomass, microbial biomass C, basal respiration, and aggregate stability) than total SOC. As discussed in Chapters One and Two, very little information is available in current literature on the use of soil C parameters to identify soils where productivity may increase in response to improved SOC management practices.
The findings and methods discussed in Weil et al. (2003) indicate that this version of the $KMnO_4$ C_L test has potential to serve as a rapid, practical field test for identifying soils where soil quality and productivity could be enhanced through improved SOC management practices.

Because of the large amount of above- and belowground biomass it produces, a winter rye (*Secale cereal* L.) cover crop can be used to increase SOC (Kuo et al., 1997;

Wagger et al., 1998). Over 6 years Kuo et al. (1997) saw a small, but detectable, increase in total SOC on plots where rye residues were incorporated via rototilling. Wagger et al. (1998) also observed increased total SOC associated with winter rye cover crop use.

Active pool SOC has shown sensitivity to the use of cover crops. The positive influence of rye or other cereal winter cover crops has been observed in microbial biomass C (Hu et al., 1997; Mendes et al., 1999; Ndiaye et al., 2000), C_{min} (Mendes et al., 1999; Sainju et al., 2000), N_{min} (Mendes et al., 1999), particulate organic matter (Hu et al., 1997), soil enzymes (Ndiaye et al., 2000) and aggregate stability (Hermawan and Bomke, 1997; Gruver, 1999).

The difficulty of quantifying relationships between SOC and soil productivity (see Chapter One and Chapter Two, Introduction) has caused researchers to instead use as surrogate indicators, soil functions that affect productivity. Water stable soil aggregates (WSA) are often used as an indicator of soil structural stability (Topp et al., 1997). In their review of physical attributes of soil quality Topp et al (1997) state that soil structure affects a soil's aeration, ability to infiltrate and hold plant available water, and resist erosion and crusting. Mineralizable N is often used as an indicator of a soil's inherent ability to supply plant-available N (Drinkwater et al., 1996). Mineralizable C is indicative of the metabolic activity of a soil's heterotrophic microbial activity, which in turn relates to a soil's ability to decompose organic wastes and plant residues (Gregorich et al., 1997). Nutrient cycling in soils depends on the microbial decomposition of these wastes and residues.

Determining C_L by $KMnO_4$ oxidation may be able to serve as an early indicator of management induced changes in SOC content. It may also be useful in identifying soils

on which crop productivity could be enhanced with improved SOC management practices. The present study was undertaken to determine if the Weil et al. (2003) procedure could be used as a soil test to ascertain where soil ecological functions are most likely to respond to improved SOC management practices, such as the use of winter cover crops. The expected responses could include enhancements in such soil quality functions as crop productivity, water infiltration, erosion resistance and nutrient cycling.

In this paper we investigated changes in soil WSA, C_L, total soil C (C_T), C_{min} and N_{min} as a result of a soil organic matter management practice, namely growing a winter rye cover crop. We hypothesized that all else being equal, a field that tests lower in C_L will benefit more (show more of an increase in soil quality responses) from improved organic matter management practices (use of winter cover crops in this case), than will a field that tests higher in C_L.

MATERIALS AND METHODS

Establishment of the experiment

Establishment and management of research plots, cover crop treatments, and related weather data is discussed extensively in the Materials and Methods section in Chapter Two. Field initial soil test results and soil classifications are given in Table 2.1. Field descriptions, layout, and specific management histories are given in Table 2.2, Figure 2.1, and Table 2.3, respectively. Cover crop and cash crop production information is available in Table 2.4. Above- and belowground biomass estimates for cover crops (and weeds in non-rye treated plots) were presented in Table 2.5. Rainfall data can be found in Figure 2.2. Because excessively wet conditions in late 2002 and early 2003

prevented significant growth of the rye planted at Upper Marboro, no cover crop treatment existed at that location and it was therefore not included in analsyis of C_{min}, N_{min} and WSA which were all conducted on soil samples from 2003.

Soil sample collection and processing

Initial soil samples were collected on 15 Oct. 2001, 16 Jan 2002 and 22 Jan. 2002, at Holtwood, Keedysville, Beltsville, respectively. Subsequent samples were taken in, Aug. 2002, Aug. 2003, and Nov. 2003 at all sites. Soil samples were extracted with a fully enclosed soil probe (JMC zero contamination probes, Clements Associates, Inc., Newton, IA) to a depth of 7.5 cm. This sampling depth was chosen because studies have shown that most of the impacts of no-till farming are seen in the shallowest sampling depths, near the rooting zone and crop residue inputs (Dick, 1983; Blevins et al., 1985; Dick et al., 1991; Potter et al. 1998). Soil was sampled by taking 14 randomly located cores from within each subplot. If cover crops or cash crops were growing, the first 7 cores were drawn from within row locations and the second 7 from between-row locations. Soil cores from each subplot were pooled and sealed in plastic lined soil sample bags. These bags were then placed under ice packs in a cooler and transported to a refrigerated storage facility. Before being stored the fresh weight of each sample was recorded to the nearest 1 g. Samples were stored in this facility at 5°C until processed. Processing took place within a month of sample collection.

For all soil samples except the Nov. 2003 samples, initial soil processing involved passing the moist soil through a 4 mm sieve by gently crumbling moist soil and shaking the sieve until all soil passed through the mesh, leaving only coarse rock or mineral

fragments on top of the mesh. Soil thus sieved was then placed on a 2 mm sieve. This sieve was gently shaken with a circular motion. For each soil sample, < 2 mm aggregates that passed through the sieve were spread out on a labeled paper plate and allowed to air dry for a period of 3 to 5 days. When completely air dry, each sample was bagged in a plastic lined paper soil sample bag, and stored at room temperature (approximately 24°C) until lab analyses were performed.

Soil from the Nov. 2003 sampling date was used for analysis of WSA by a procedure requiring 1-4mm aggregates and therefore initial processing for these samples was slightly different. After passing the 4 mm sieve, approximately 2/3 of the soil was placed on a 2mm sieve and sieved as described above. The remaining 1/3 was placed on a 1mm sieve and sieved as described for soil passed through the 2 mm sieve. The portion that remained on top of the 1 mm mesh comprised the 1–4 mm aggregates for analysis of WSA. The < 2mm fraction was used in all other lab analyses.

Soil analyses

Once processed, particle size analysis was performed on the initial samples using a modified pipette method. Total C (C_T) was analyzed on the initial samples with a LECO high temperature combustion analyzer (Tabatabai and Bremner, 1991). Mineralizable C and N_{min} were determined on Aug. 2003 samples as described below. The WSA percentage was assessed on Nov. 2003 samples as described below.

Incubation procedure for mineralizable C and mineralizable N

Soil incubation for the simultaneous determination of N_{min} and C_{min} was performed on 10g subsamples of the <2 mm fraction of air-dried soil from the Aug. 2003 sampling. These samples were moistened to 60 % water-filled pore space and incubated in sealed 947ml containers at 30 °C in the dark for 16 days using a modified aerobic incubation procedure (Drinkwater et al., 1996). Each container held a small beaker with 4.0ml 0.5*M* NaOH to capture CO_2-C evolved and 20 mL distilled water in another beaker to maintain 100% humidity and prevent soil drying. Four blanks that contained NaOH and water beakers, but no soil, were also prepared to measure background CO_2.

Mineralizable C determination

At 1, 2, 4, 8, and 16 days of incubation, the CO_2 trap was removed from the incubation container. Coinciding with this trap removal was the replacement of the incubated CO_2 trap with a new trap containing a fresh 4.0ml of 0.5*M* NaOH. Incubated CO_2 traps were treated with 4 ml of 0.5 *M* $BaCl_2$ to stop further CO_2 neutralization of NaOH. The base traps were titrated with a solution of 0.15*M* HCl and the amount of CO_2-C was determined as described in Anderson (1982). To determine the amount of CO_2 actually evolved from soil samples, the average amount of CO_2 absorbed in the blanks at 1, 2, 4, 8, and 16 days, respectively, was subtracted from the amount of CO_2 absorbed in each NaOH trap from containersin which soil was incubated The cumulative C_{min} after 2 days ($C_{min\text{-}2d}$) was determined to be a good representation of active pool SOM, based on Franzluebbers et al. (2000).

Mineralizable N determination

To determine mineralized N, both incubated (16 days) and non-incubated soil was extracted with 20 ml 0.1*M* K_2SO_4 and nitrate-N determined by a modified salicylic acid method (Cataldo et al., 1975). Ammonium-N in these soil extracts was determined on an Orion model 940 ion analyzer (Orion Research Inc., Beverly, MA) by ammonia-specific electrode (VWR Scientific Products, West Chester, PA), after adding 1 ml of 5*M* NaOH to 10 ml of soil extract to raise the pH above 13 (Easton, 1976). Nitrate-N_{min} (NO_3-N_{min}) in soil extracts was calculated as:

$$NO_3\text{-}N_{min}\ (ppm) = NO_3\text{-}N_{IS}\ (ppm) - NO_3\text{-}N_{NS}\ (ppm)$$

where NO_3-N_{IS} (ppm) is NO_3-N extracted from incubated soils and NO_3-N_{NS} (ppm) is NO3-N extracted from non-incubated air-dry soils. Ammonium-N_{min} (NH_4-N_{min}) in soil extracts was calculated as:

$$NH_4\text{-}N_{min}\ (ppm) = NH_4\text{-}N_{IS}\ (ppm) - NH_4\text{-}N_{NS}\ (ppm)$$

where NH_4-N_{IS} (ppm) is NH_4-N extracted from incubated soils and NH_4-N_{NS} (ppm) is NH_4-N extracted from non-incubated soils. Soil N_{min} was calculated as:

$$N_{min}(ppm) = \left(NO_3\text{-}N_{min}(ppm) + NH_4\text{-}N_{min}(ppm)\right) * \left(\frac{20\ ml\ K_2SO_4}{W_{dc}}\right)$$

where W_{dc} is the calculated oven dry mass of soil used. This term was calculated using the gravimetric moisture content (θg) of each air dried Aug. 2003 soil sample as:

$$W_{dc}\ (g) = 10g\ air\ dried\ soil * (1 - \theta g)$$

Gravimetric moisture content was determined by oven drying a 5g subsample of each air dried soil sample and calculating as:

$$\theta g = \frac{W_w - W_d}{W_d}$$

where W_w is the mass of air dried soil and W_d is the mass of oven dried soil.

Determination of aggregate stability in water

The percentage of WSA was determined on 1-4 mm size aggregates from the Nov. 2003 samples by a modification of the Kemper and Roseneau (1986) method as described in Gruver and Weil (1998). For this analysis approximately 5 g of air-dry soil was weighed (recorded to the nearest 0.01 g). This soil was placed on a sieve having 0.73 mm openings. The sieve and soil were submerged in 100 ml of distilled water in a pre-weighed (±0.001 g) 500 ml plastic container. This container was shaken horizontally for 2 minutes on an orbital shaker set to 100 rpm. After shaking the sieve was removed from the first plastic container and placed into a second pre-weighed (±0.001 g) 500 ml plastic container that also held 100 ml distilled water. All of the soil aggregates that remained on the sieve after initial shaking were forced through the sieve, into the second container while mineral fragments >0.73mm remained on the sieve. The sieve was removed from the second cup, and the soil in the cup wasdried at 80°C. The sieve was removed from the second cup, and the soil in the cup dried at 80°C and reweighed (± 0.001 g). The percent WSA was calculated as:

$$\mathrm{WSA\%} = \frac{100 * (c2)}{(c1 + c2)}$$

where c1 is the mass of soil that passed through the 0.73 mm sieve and was collected in the first cup and c2 is the mass of soil forced through the sieve and collected in the second cup.

Estimation of soil response to cover crop treatment

The soil functional response to cover crop treatment in blocks within management histories within each site was calculated for N_{min}, C_{min}, and WSA. At each of four sites, a field having sod management history (MH_{sod}) and a field having cropped management history (MH_{crop}) were paired and divided into four blocks, each block containing one plot with a rye winter cover ($COVER_{rye}$) and one without ($COVER_{bare}$). The response was defined as the difference between $COVER_{rye}$ plots and $COVER_{bare}$ plots within each block.

To assess relationships between soil functional response parameters and soil C parameters across more than one site, the soil functional responses were assessed on a relative basis by converting the response calculated as described above to a percent change. This was done as follows:

$$\text{Relative Response (\%)} = \left(\frac{X_{\text{i-rye}} - X_{\text{i-bare}}}{X_{\text{i-bare}}} \right) * 100$$

where $X_{i\text{-rye}}$ is the observed value for the soil function in $COVER_{rye}$ plots and $X_{i\text{-bare}}$ is the observed value for the soil function in $COVER_{bare}$ plots.

Correlations were calculated between the response parameters and the initial soil C measurements expressed as C_L or C_T or the ratios of C_L or C_T to soil silt+clay content ($C_{L/Fines}$ or $C_{T/Fines}$).

Statistical analyses

Analyses of variance using a split plot model with C_L, C_T, N_{min}, $C_{min\text{-}2d}$, and WSA as dependent variables were performed. The whole-plots were fields of contrasting MH and subplots were cover crop treatments.

The error term and degrees of freedom associated with (BLOCKS(MH)) was used to test whole-plot (field MH) effects within a single site. To test effects of cover crop treatment (COVER) and the interaction COVER*MH within a site, the error term and degrees of freedom used were those associated with the interaction COVER*(BLOCKS(MH)). Inferences on effects seen at an indiviualsite level should not be made beyond that site because at each site the replication occurs at the level of blocks within contrasting fields. These blocks are not true replicates because the four blocks within each MH are not statistically independent. Each block is a pair of observations ($COVER_{rye}$ or $COVER_{bare}$) within the same experimental unit (a field of a specific MH). Thus, per Hurlbert (1984), these blocks are pseudoreplicates at the individual site level. True replication in this experiment occurs when data is analyzed across all sites.

When ANOVA was performed across all sites, each site represents a true, independent replication and each block nested within MH field represents two cover crop treatments (rye and no rye) within that field and site. When ANOVA was performed across all sites, the error and degrees of freedom used for testing whole-plot effects were those associated with (BLOCKS(MH(SITE))). When testing subplot effects and whole-plot by subplot interactions the error term and degrees of freedom used were those associated with COVER*(BLOCKS(MH(SITE))).

Analysis of variance on initial C_T, $C_{T/Fines}$, initial C_L, and $C_{L/Fines}$ were analyzed using a split plot model similar to that described above for other soil function parameters. Since soil sampling was performed before significant growth cover crops COVER effects and COVER*MH interactions were not considered, however since each COVER subplot within (BLOCKS(MH)) was sampled for C_T and C_L each subplot was left in the model as an observation within (BLOCKS(MH)).

Of particular interest in this research is the interaction between whole-plots and subplots. Significant interaction could be an indication that crops are responding differently to COVER in fields differing in MH.

Analysis of variance on response variables across all sites was performed using a randomized complete block design where each SITE is also a replication and the dependent response variable was tested against (MH(SITE)). Since specific field management histories were unique to each site, it was deemed most appropriate to nest MH within SITE for these analyses. When nesting in this manner, overall response means for MH could not be generated, however the overall significance of (MH(SITE)) was tested across all sites. Again, because of the pseudoreplication of (BLOCKS(MH)) at the individual site level, conclusions drawn at the individual site level should not be inferred beyond that site. Response variables at each individual site were tested against MH.

Correlation analyses were used to examine relationships between soil C parameters and soil functional response parameters. Pearson correlation coefficients are presented. For scatterplots of two correlated variables, a Gaussian bivariate confidence ellipse (P= 0.6827) is drawn to show the nature of the relationship between the two

variables (Systat, 2002). It is centered on the sample means of the x and y variables with the unbiased sample standard deviations of x and y determining its major axes and the sample covariance between x and y, its orientation.

All statistical analyses were performed using SYSTAT version 10 (SYSTAT 2002).

RESULTS AND DISCUSSION

Total C and $KMnO_4$ Labile Soil C

Initial C_T and C_L were significantly different between MH_{sod} and MH_{crop} at all sites (Chapter 2, Table 2.10). The MH_{sod} fields had 87%, 114%, and 80% greater C_T than MH_{crop} fields at Beltsville, Keedysville, and Holtwood, respectively. The MH_{sod} fields had 39%, 79%, and 36% greater C_L than MH_{crop} fields at Beltsville, Keedysville, and Holtwood, respectively. These results were expected and were essential to testing the hypothesis of higher soil function response in fields that test lower in C_L.

Total soil C changes very slowly in response to management but changes in C_L may be harbingers for change in C_T (Islam and Weil, 2000). Although there was a close relationship between C_L and C_T (Chapter 2, Figure 2.3), no significant COVER*MH interactions were seen for C_T at any site or when the data was analyzed across all sites.

Analysis of Mineralizable C, Mineralizable N, and Percent Water Stable Aggregates

For soil sampled in August, 2003 after two years of rye cover crop treatment, **c**umulative C mineralized during two days of incubation was significantly different between fields of contrasting MH at Beltsville and Keedysville (Table 3.1). The amount

of C_{min-2d} was 96% and 95% greater in MH_{sod} fields than in MH_{crop} fields at Beltsville and Keedysville, respectively. At Holtwood, C_{min-2d} did not differ significantly between fields, possibly because both the MH_{crop} and MH_{sod} fields at this site had been in no-till crops for 10 years prior to the inception of this study, thus reducing the effect of management history on the soil C and microbial populations between these fields. When analyzed across all sites the difference in C_{min-2d} between fields of contrasting MH was statistically significant.

Tests for COVER*MH interaction effects on C_{min-2d} showed a highly significant ($P<0.01$) interaction at Holtwood (Table 3.1). $COVER_{rye}$ plots in the MH_{crop} field at Holtwood had 42% more C mineralization than $COVER_{bare}$ plots. In the sod history field at Holtwood, $COVER_{rye}$ plots had only 3% more C_{min-2d} than $COVER_{bare}$ plots. The COVER*(MH(SITE)) interaction was significant ($P = 0.049$) when tested across all sites (Table 3.1).

The effect of field MH on N_{min} in Aug. 2003 soil samples was not significant at any individual site nor was the overall effect of (MH(SITE)) on N_{min} significant. The COVER*MH interaction effect on N_{min} was significant only at Holtwood (Table 3.1), possibly because of the longer period of cover crop treatments at this site. At Holtwood $COVER_{rye}$ plots in the MH_{crop} field had 30% greater N_{min} than $COVER_{bare}$ plots. In the MH_{sod} field $COVER_{rye}$ plots had approximately 2% lower N_{min} than that observed in $COVER_{bare}$ plots. When analyzed across all sites, the interaction COVER*(MH(SITE)) was not significant.

The percentage of WSA was significantly higher in sod history fields at Keedysville and Holtwood (Table 3.1). There were 234% and 42% more WSA in sod

history fields at Keedysville and Holtwood, respectively than in cropped history fields at these sites. The significance of differences in percent WSA at these sites is likely due in part to the higher soil clay content at these sites (Chapter 2, Table 2.1). Interactions between clay and SOM have been observed to play an important role in soil aggregation dynamics (Tisdall and Oades, 1982). The effect of MH at Beltsville, while not significant, followed the same pattern. When analyzed across all sites the overall effect of MH on percent WSA was highly significant.

A significant COVER*MH interaction on WSA, observed in soils from Keedysville, resulted in a 135% greater WSA in $COVER_{rye}$ plots in the MH_{crop} field but only a 1.1% greater WSA in $COVER_{rye}$ plots in the MH_{sod} field The COVER*MH interaction was not significant at Beltsville or Holtwood. The interaction COVER*(MH(SITE)) was not significant when tested across all sites.

Relationships between soil C parameters and soil functional parameters

Soil $C_{min\text{-}2d}$ was strongly positively related to both C_L and C_T (Figure 3.1). The correlation of $C_{min\text{-}2d}$ with C_L was slightly closer (r= 0.75) than with C_T, (r=0.71). The C_T relationship seems to agree with previous work by Biederbeck et al. (1994) who found C_{min} to be related to C_T. Franzluebbers et al. (2000) found C_{min} (in 3 days) to be more strongly related to labile soil parameters such as microbial biomass C than to C_T. The relationship with C_L agrees with Weil et al. (2003) who found 0.02*M* $KMnO_4$ oxidizable C to be more closely related to microbial activity than C_T.

Mineralizable N was weakly related with both C_T and C_L (Figure 3.2). The correlation of N_{min} with C_L (r =0.588) was only slightly closerthan that with C_T (r = 0.503). Since N_{min} is a product of microbial catabolism, this positive relationship also suggests that 0.02*M* $KMnO_4$ oxidizable C is more closely related than C_T to microbial acitivty.

Both C_L and C_T were significantly related to WSA (Figure 3.3). Though not as strong, the positive relationship between WSA and C_L agrees with previous work by Stine and Weil (2002) and Weil et al. (2003), who found 0.02*M* $KMnO_4$ oxidizable C to be closely related to WSA. The positive relationship between C_T and aggregate stability has long been established (Tisdall and Oades, 1982; Elliott, 1986).

Soil function responses to rye cover crop

After two winter rye cover crops there was no significant WSA response to rye at any site or when analyzed across all sites (Table 3.2). The response of N_{min} to rye was significant at Holtwood, where N_{min} showed a positive response to rye in the MH_{crop} field but no significant response in the MH_{sod} field (Table 3.2). One response observation in the MHsod field at Keedysville was an outlier (Studentized residual = 2.80) in the analysis of N_{min}. When this observation was removed from the analysis the overall effect of (MH(SITE)) on response was significant (P = 0.008). At Holtwood, $C_{min\text{-}2d}$ response to rye was significantly greater in the MH_{crop} field where the response to rye was 11 fold greater than the response in the MH_{sod} field (Table 3.2). The Cmin-2d response to rye was significant across all sites due to the highly significant effect seen at Holtwood.

When Holtwood was removed from the overall analysis, the C_{min-2d} response to rye was not significant.

Relationships between soil functional responses and soil C parameters

When analyzed across all sites, relative WSA response to rye was significantly and negatively correlated with initial C parameters only if they were normalized for texture ($C_{L/Fines}$ and $C_{T/Fines}$) (Table 3.3). If the sandy site (Beltsville) was removed, the correlation of WSA response with C parameters was significant and little affected whether or not the C was normalizing for soil fines (data not shown). At individual sites, WSA response to rye was significantly and negatively related to C_L and C_T at Keedysville (Table 3.3), meaning that rye had a greater effect on WSA where intial C_L and C_T were relatively low.

Relative N_{min} response to rye was significantly and negatively correlated with both intial C_L and C_T when analyzed across all sites (Table 3.3). Analysis of individual sites showed a significant correlation of N_{min} response with C_L and C_T only at Holtwood (Table 3.3). All correlations between N_{min} response parameters and C parameters were negative, meaning that rye cover cropping increased N_{min} more where C_L and C_T were relatively low. Normalizing for soil fines actually reduced the correlations, so that N_{min} was more not significantly correlated with $C_{L/Fines}$ or with $C_{T/Fines}$. This suggests that part of the correlation between initial C parameters and N_{min} is a function of soil texture effects on initial C.

No significant relationships were observed between relative C_{min-2d} response and C_L, C_T, $C_{L/Fines}$, or $C_{T/Fines}$ when analyzed across all sites (Table 3.3). For analyses at

individual sites, only at Holtwood was the C_{min-2d} response to rye was significantly correlated with C_L and C_T (Table 3.3) and the correlation was negatively.

Whether analyzed across all sites or at individual sites, the strength of soil response parameter correlations with C_L or $C_{L/Fines}$ was similar to the strength of correlations with C_T or $C_{T/Fines}$ respectively. Cover crop treatments at Holtwood had been in place since 1998, so the large positive responses to rye at this site were the result of the cumulative effects of four more years of cover crop treatments compared to two years at the other sites.

CONCLUSIONS

This study builds on previous work by Weil et al. (2003) in relating C_L to other soil parameters indicative of a biologically active pool of SOM. Labile soil C was positively related to C_{min-2d}, N_{min}, and WSA. The C_L relationships with C_{min-2d}, and N_{min} were slightly stronger than those with C_T. The C_L relationship with WSA was slightly weaker than that with C_T although the difference is so small that it may be difficult to determine which soil C parameter is a better predictor of WSA.

In predicting soil functional responses to rye cover crops, C_L parameters were generally comparable to C_T parameters when significant relationships were seen. The results of this study do not show any soil C parameter that is clearly a better predictor than the others. Where significant response relationships were observed with soil C parameters greater responses coincided with lower levels of soil C parameters. Greater significant soil functional responses to rye were seen in fields where C_T tested between 9.4 g kg^{-1} and 16.8 g kg^{-1} and C_L tested between 374 mg kg^{-1} and 573 mg kg^{-1}. In fields

where C_T tested between 17.5 g kg^{-1} and 30.3 g kg^{-1} and C_L tested between 521 mg kg^{-1} and 778 mg kg^{-1} the positive response to rye cover crop treatment was less. These results support the conclusion that soils having lower SOC content benefited more from rye cover crops than soils that tested high in SOC content. Given these results, the results of Chapter 2, and the fact that no field-practical test for C_T has been developed, the Weil et al. (2003) $KMnO_4$ method for assessing C_L shows significant promise as an SOC test to be included in a field testing kit for assessing soil quality, such as that currently offered by the NRCS.

REFERENCES

Alvarez, C.R., R. Alvarez, M.S. Grigera, and R.S. Lavado. 1998. Associations between organic matter fractions and the active soil microbial biomass. Soil Biol. and Biochem. 30:767-773.

Anderson, J.P.E. 1982. Soil respiration. p. 837-871. In A.L. Page et al. (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Biederbeck, V.O., H.H. Janzen, C.A. Campbell, R.P. Zentner. 1994. Labile soil organic matter as influenced by cropping practices in an arid environment. Soil Biol. Biochem. 26:1647-1656

Blevins, R.L., W.W. Frye, and M.S. Smith. 1985. The effects of conservation tillage on soil properties. p. 99-110. In F.M. D'Itri (ed.) A systems approach to conservation tillage. Lewis Publishers, Chelsea, MI.

Blair, G.J., R.D.B. Lefroy, and L. Lisle. 1995. Soil carbon fractions based on their degree of oxidation and the development of a carbon management index for agricultural systems. Aust. J. Agric. Res. 46:1459-1466.

Cambardella, C.A., and E.T. Elliot, 1992. Particulate soil organic matter changes across a grassland cultivation sequence. Soil Sci. Soc. Am. J. 56:777-783.

Cambardella, C.A., and E.T. Elliot, 1993. Carbon and nitrogen distribution in aggregates from cultivated and native grassland soils. Soil Sci. Soc. Am. J. 57:1071-1076.

Cataldo, D.A., M Haroon, L.E. Schrader, and V.L. Young. 1975. Rapid colorimetric determination of nitrate in plant tissue by nitration of salicylic acid. Comm. Soil Sci. Plant Anal. 6:71-80.

Christensen, B.T. 1992. Physical fractionation of soil and organic matter in primary particle size and density separates. p. 1-90. *In* Advances in soil science, Vol. 20. Springer-Verlag, New York.

DeLuca, T.H., and D.R. Keeney. 1994. Soluble carbon and nitrogen pools of prairie and cultivated soils: Seasonal variation. Soil Sci. Soc. Am. J. 58:835-840.

Dick, R.P. 1992. A review: long-term effects of agricultural systems on soil biochemical and microbial parameters. Agric. Ecosys. Environ. 40:25-36.

Dick, W.A. 1983. Organic carbon, nitrogen, and phosphorus concentrations and pH in soil profiles as affected by tillage intensity. Soil Sci Soc, Am. J. 47:102-107.

Dick, W.A., E.L. McCoy, W.M. Edwards, and R. Lal. 1991. Continuous application of no-tillage to Ohio soils. Agron J. 83:65-73.

Dick, W.A., and E.G. Gregorich. 2004. Developing and maintaining soil organic matter levels. p. 103-120. *In* P. Schjonning, S. Elmholt, and B.T. Christensen (ed.) Managing Soil Quality: Challenges in modern agiculture. CABI Publishing, Oxon, United Kingdom.

Drinkwater, L.E., C.A. Cambardella, J.D. Reeder, and C.W. Rice. 1996. Potentially mineralizable nitrogen as an indicator of biologically active soil nitrogen. p. 203-229. *In* J.W. Doran, and A.J. Jones (ed.) Methods for assessing soil quality. SSSA Spec. Publ. 49. SSSA, Madison, WI.

Easton, E.F. 1976. Use of ammonium electrode for total nitrogen determination in plants. Comm. Soil Sci. Plant Anal. 3:477-481.

Elliot, E.T. 1986. Aggregate structureand carbon, nitrogen, and phosphorus in native and cultivated soils. Soil Sci. Soc. Am. J. 50:627-633.

Franzluebbers, A.J., R.L. Haney, C.W. Honeycutt, H.H. Schomberg, and F.M. Hons. 2000. Flush of carbon dioxide following rewetting of dried soil relates to active organic C pools. Soil Sci. Soc. Am. J. 64:613-623.

Gregorich, E.G., M.R. Carter, D.A. Angers, C.M. Monreal, and B.H. Ellert. 1994. Towards a minimum data set to assess soil organic matter quality in agricultural soils. Can. J. Soil Sci. 74:367-385.

Gregorich, E.G., M.R. Carter, J.W. Doran, C.E. Pankhurst. 1997. Biological attributes of soil quality. p.81-113. *In* E.G. Gregorich and M.R. Carter (ed.) Soil quality for crop production and ecosystem health. Elsevier Science Publishers B.V., Amsterdam, The Netherlands.

Gruver, J.B., and R.R. Weil. 1998. Simplified method for determination of aggregate stability for soil quality assessment, pp. 220 1998 Agronomy abstracts. ASA, Madison, WI.

Gruver, J.B. 1999. Relationships between farmer perceptions of soil quality and management sensitive soil parameters. M.S. Thesis. University of Maryland, Colllege Park, MD.

Hermawan, B., and A.A. Bomke. 1997. Effects of winter cover crops and successive spring tillage on soil aggregation. Soil Tillage Res. 44:109-120.

Hurlbert, S.H. 1984. Pesudoreplication and the design of ecological field experiments. Ecol. Monogr. 54:187-211.

Hu, S., N.J. Grunwald, A.H.C. van Bruggen, G.R. Gamble, L.E. Drinkwater, C Shennan, and M.W. Demment. 1997. Short-term effects of cover crop incorporation on soil carbon pools and nitrgen availability. Soil Sci. Soc. Am. J. 61:901-911.

Islam, K.R. and R.R. Weil. 2000. Soil quality indicator properties in mid-Atlantic soils as influenced by conservation management. J. Soil Water Conserv. 55:69-78.

Jenkinson, D.S. 1988a. Determination of microbial biomass carbon and nitrogen in soil. p. 368-386. *In* J.R. Wilson (ed.) Advances in nitrogen cycling in agricultural ecosystems. CABI Publishing, Oxon, England

Jenkinson, D.S. 1988b. Soil organic matter and its dynamics. p. 564-607. *In* A. Wild (ed.) Russell's soil conditions and plant growth. 11th ed. Longman, New York.

Karlen, D.L., N.S. Eash, and P.W.Unger. 1992. Soil and crop management effects on soil quality indicators. Am J. Altern. Agric. 7:48-55.

Kemper, W.D. and R.C. Rosenau. 1986. Aggregate stability and size distribution. p. 425-442. *In* Methods of soil analysis, Part 1. Physical and Mineralogical Methods—Agronomy Monograph no. 9. 2nd edition. Agronomy Society of America, Madison, WI.

Kennedy, A.C., and R.I. Papendick. 1995. Microbial characteristics of soil quality. J. Soil Water Conserv. 50:243-248.

Kortleven, J. 1963. Quantitative aspects of humus accumulation and decomposition. Versl. Landb. Ond. nr. 69.1 PUDOC, Wageningen (in Dutch).

Kuo, S., Sainju, U.M., and E.J. Jellum. 1997. Winter cover crop efects on soil organic carbon and carbohydrate in soil. Soil Sci. Soc. Am. J. 61:145-152.

Larson W.E., and F.J. Pierce. 1994. The dynamics of soil quality as a measure of sustainable management. p. 37-51. *In* J.W.Doran, D.C. Coleman, D.F. Bezdicek, and B.A. Stewart (ed.) Defining soil quality for a sustainable environment. SSSA Spec. Publ. 35. SSSA, Madison, WI.

Liebig, M.A. and J.W. Doran. 1999. Evaluation of farmers' perceptions of soil quality indicators. Am. J. Alt. Agric. 14:11-21.

Mendes, I.C., A.K. Bandick, R.P. Dick, and P.J. Bottomley. 1999. Microbial biomass and activities in soil aggregates affected by winter cover crops. Soil Sci. Soc. Am. J. 63:873-881.

Potter, K.N., H.A. Tolbert, O.R. Jones, J.E. Matocha, J.E. Morrison, and P.W. Unger. 1998. Distributionan amount of soil organic C in long-term management systems in Texas. Soil Tillage Res. 47:309-321.

Saviozzi, A., A. Biasci, R. Riffaldi, and R. Levi-Minzi. 1999. Long-term effects of farmyard manure and sewage sludge on some soil biochemical characteristics. Biol. Fertil. Soil. 30:100-106.

Seybold, C.A., M.J. Mausbach, D.L. Karlen, and H.H. Rogers. 1996. Quantification of soil quality. p.53-68. *In* T.S.Q. Intitute (ed.) The soil quality concept. USDA/NRCS, Washington, D.C.

Sikora, L.J., and D.E. Stott. 1996. Soil Organic Carbon and Nitrogen. p. 157-167. *In* J.W.Doran and A.J. Jones (ed.) Methods for assessing soil quality. SSSA Spec. Publ. 35. SSSA, Madison, WI.

Stine, M.A., and R.R. Weil. 2002. The relationship between soil quality and crop productivity across three tillagesystems in south central Honduras. Am. J. Altern. Agric. 17:2-8.

Tabatabai, M.A., and J.M. Bremner. 1991. Automated instruments for determination of total carbon, nitrogen, and sulfur in soils by combustion techniques. p. 261-286. *In* K.A. Smith (ed.) Soil analysis: Modern instrumental techniques. 2nd ed. Dekker, New York.

Topp, G.C., W.D. Reynolds, F.J. Cook, J.M. Kirby, and M.R. Carter. 1997. Physical attributes of soil quality. p. 21-58. *In* E.G. Gregorich and M.R. Carter (ed.) Soil quality for crop production and ecosystem health. Elsevier Science Publishers B.V., Amsterdam, The Netherlands.

Tisdall, J.M., and J.M. Oades. 1982. Organic matter and water stable aggregates in soils. J. Soil Sci. 33:141-163.

Wagger, M.G., M.L. Cabrera, and N.N. Ranells. 1998. Nitrogen and carbon cycling in relation to cover crop residue quality. J. Soil Water Conserv. 53:214-218.

Wander, M.M., S.J. Traina, B.R.Stinner, an S.E. Peters. 1994. Organic and conventional management effects on biologically active soil organic matter pools. Soil Sci. Soc. Am. J. 8:1130-1139.

Wander, M.M., and M.G. Bidart. 2000. Tillage practice influences on the physical protection, bioavailability and composition of particulate organic matter. Biol. Fertil. Soils 32:360-367.

Wander, M.M., and L.E. Drinkwater. 2000. Fostering soil stewardship through soil quality assessment. Appl. Soil Ecol. 15:61-73.

Weil, R.R., K.R. Islam, M.A. Stine, J.B. Gruver, and S.E. Samson-Liebig. 2003. Estimating active carbon for soil quality assessment: A simplified method for lab and field use. Am. J. Altern. Agric. 18:3-17.

FIGURES AND TABLES

Table 3.1. Sitewise mean values for $C_{min\text{-}2d}$, N_{min}, and percent water stable aggregates in fields of contrasting management history and in cover crop treatment levels within these fields. The overall effects (across all sites) of field management history (FMH) nested within site and interaction between cover crop treatment and field management history nested within site are also presented.

	Field Management History			Cover crop treatment within Field Management History				
				Cropped			Sod	
Site	Cropped		Sod	Rye	No Rye		Rye	No Rye
	Cumulative C mineralized after 2 days of incubation							
	mg kg^{-1}							
Beltsville	74.41	**	146.12	77.54	71.28		154.87	137.38
Keedysville	207.11	***	404.87	228.83	185.39		441.55	368.18
Holtwood	295.92		275.79	346.93	244.91	†	280.27	271.31
Overall effects‡		MH within site				Interaction		
		***				†		
	Mineralizable N							
	mg kg^{-1}							
Beltsville	33.32		30.53	42.43	24.21		31.85	29.20
Keedysville	85.48		94.26	105.17	65.79		104.35	84.18
Holtwood	159.10		148.76	179.69	138.50	†	147.34	150.18
Overall effects‡		MH within site				Interaction		
		NS§				NS§		
	Water Stable Aggregates							
	%							
Beltsville	66.14		80.90	66.13	66.16		82.80	79.01
Keedysville	25.74	***	86.00	36.11	15.36	†	86.49	85.50
Holtwood	54.02	**	76.60	59.56	48.50		85.34	67.85
Overall effects‡		MH within site				Interaction		
		***				NS§		

*, **, *** For site means: Indicates means different at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively. For overall effects indicates significance of effect at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

† For site means: Indicates significant interaction between cover crop treatment and FMH at $P < 0.05$. For overall effects indicates significant interaction between cover crop treatments and FMH when tested across all sites.

‡ Overall effects of MH(SITE) tested across all sites and the interaction COVER*(MH(SITE)) tested across all sites. Overall significance can be tested but individual means can not be generated due to nested nature of variables.

§ NS: Not Significant.

Table 3.2. Mean soil function responses ($COVER_{rye}$ – $COVER_{bare}$) to cover crop treatment within fields of contrasting management history at three research sites.

Site	Field Management History		Field Management History		Field Management History	
	Cropped	Sod	Cropped	Sod	Cropped	Sod
	C_{min-2d} Response		N_{min} Response		WSA Response	
	mg kg^{-1}		mg kg^{-1}		%	
Beltsville	6.26	17.50	18.23	2.66	-0.03	3.78
Keedysville	43.44	73.37	39.38	20.18	20.74	1.00
Holtwood	102.02	8.96	41.19	-2.84	11.07	17.49
Overall effect of MH within site‡	**	*	*	**§	NS†	

* Means significantly different at $P < 0.05$.

§ Outlier (Studentized residual = 2.80) was removed from data. Effect is not significant when the outlier is included.

‡ Overall significance of the effect of (MH(SITE)) on crop response tested across all sites (* Significant effect at $P < 0.05$).

† NS: No statistically significant effect.

Figure 3.1. The relationships between C mineralized in 2 days (C_{min-2d}) and (A) total soil C, C_T and (B) labile soil C, C_L. Data are for soil sampled at three research sites after two years of rye cover crop treatments. The Guassian bivariate confidence ellipse has P=0.6278 and *** indicates correlation is significant at P < 0.001.

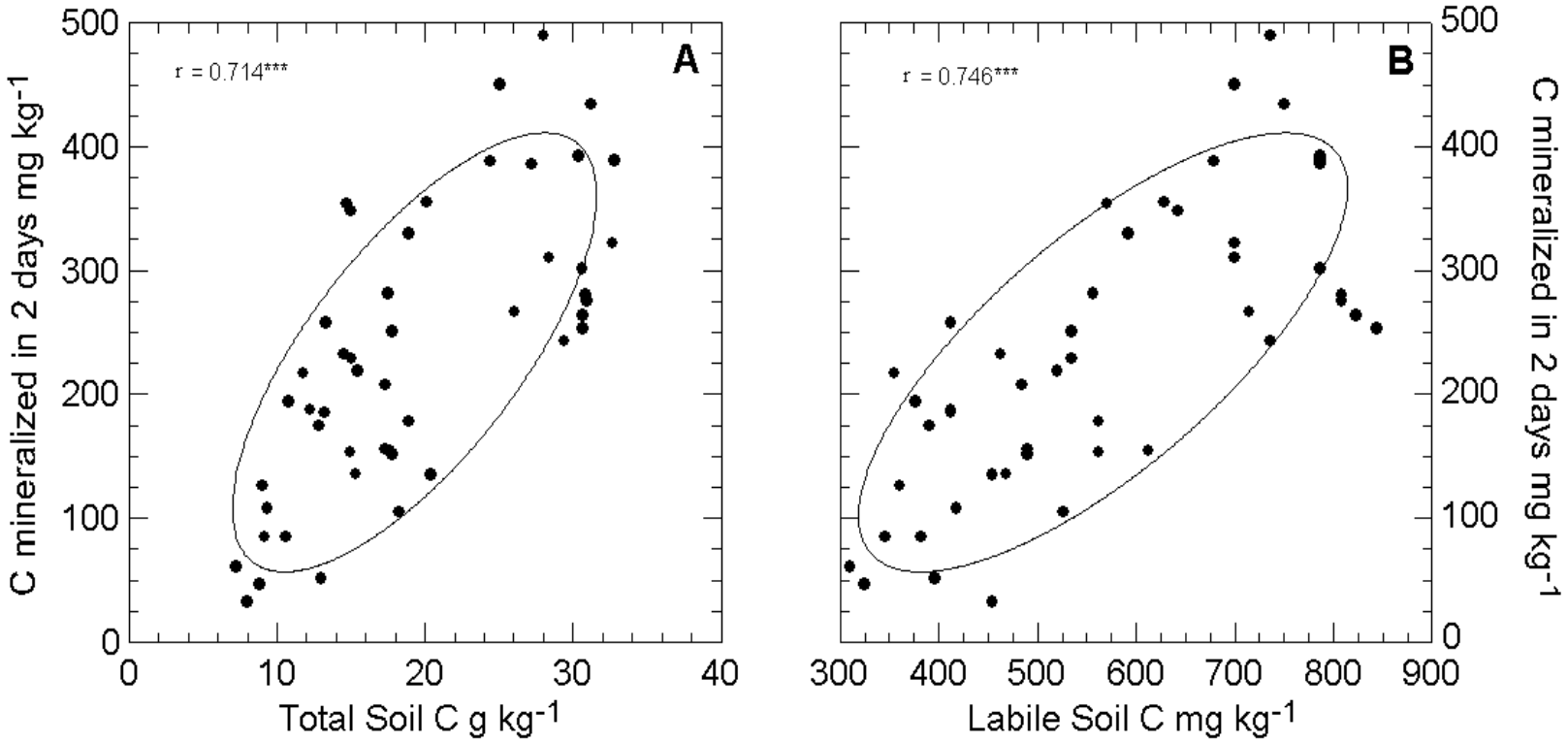


Figure 3.2. The relationships between mineralizable N (N_{min}) and (A) total soil C, C_T and (B) labile soil C, C_L. Data are for soil sampled at three research sites after two years of rye cover crop treatments. The Guassian bivariate confidence ellipse has P=0.6278 and *** indicates correlation is significant at P < 0.001.

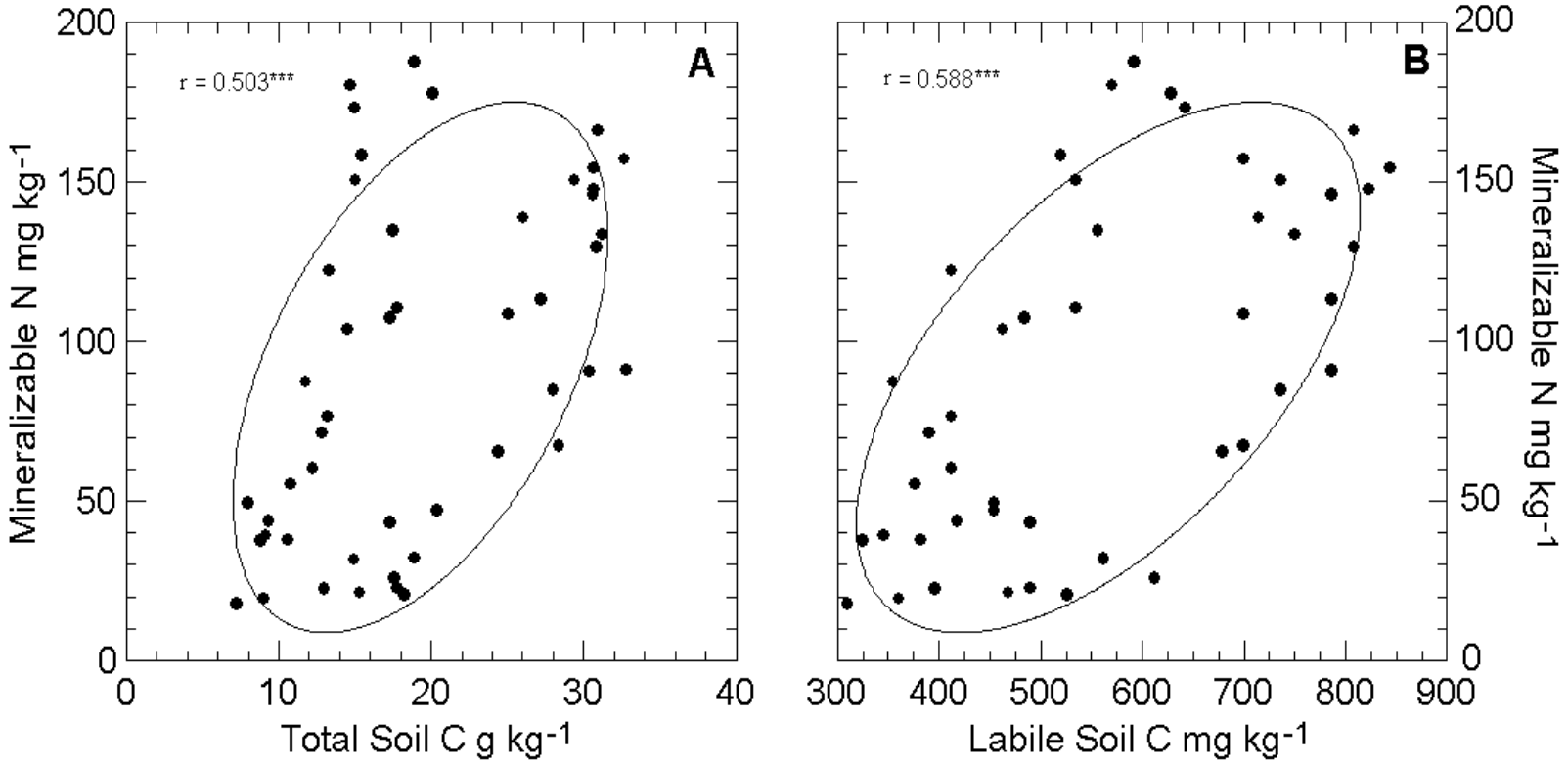


Figure 3.3. The relationships between percent water stable soil aggregates (WSA) and (A) total soil C, C_T and (B) labile soil C, C_L. Data are for soil sampled at three research sites after two years of rye cover crop treatments. The Guassian bivariate confidence ellipse has P=0.6278 and *** indicates correlation is significant at P < 0.001.

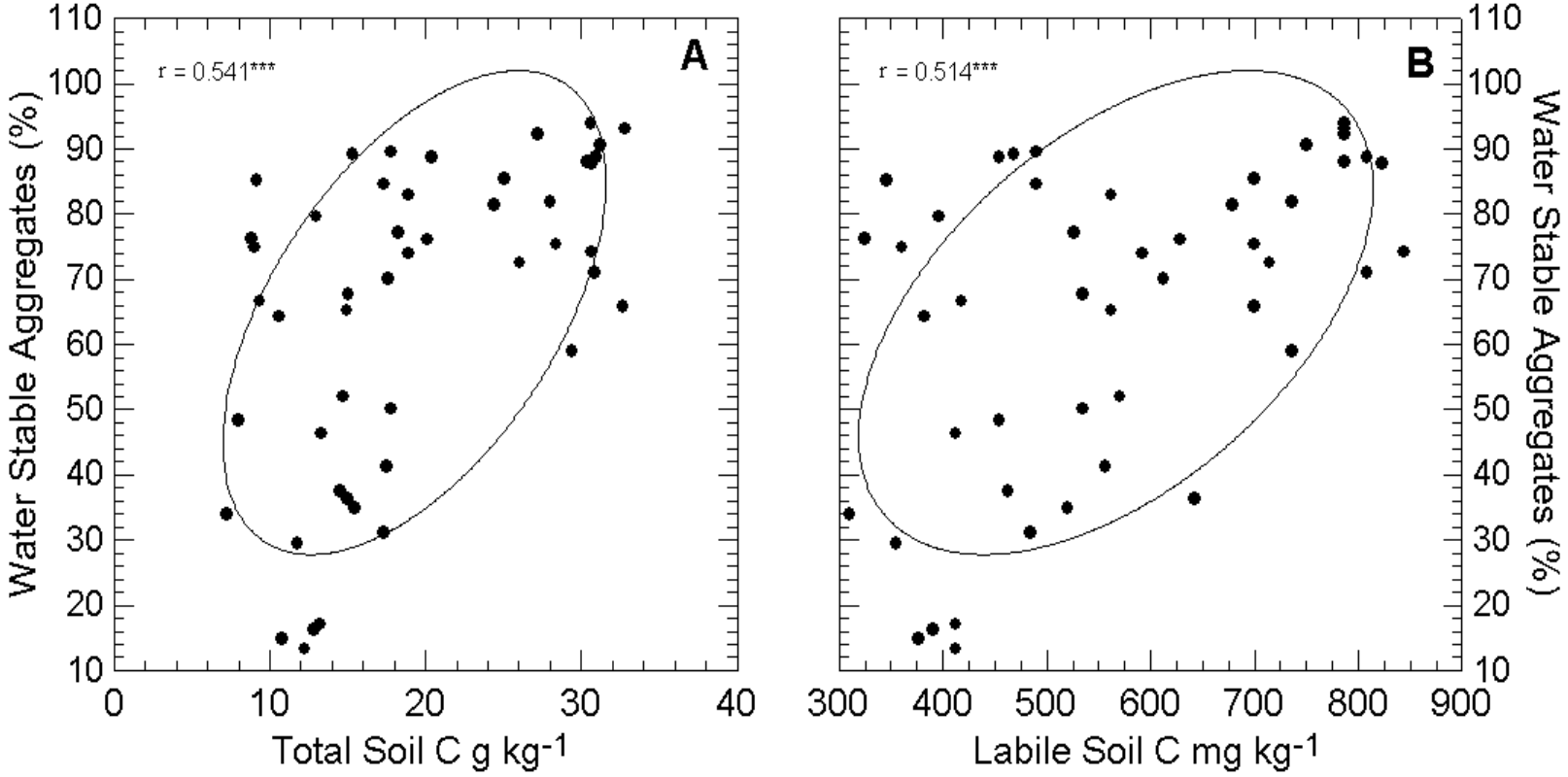


Table 3.3. Correlations between soil functional responses to rye cover crops and soil C parameters across all sites, and within individual sites. In analyses across all sites, the response relationships are for relative responses (see Materials and Methods). At individual sites the response was related directly to measured soil C parameters.

Soil C Parameter	Cmin-2d response	Nmin response	WSA response
	Correlation coefficient (r)		
	All Sites†		
C_L	-0.143	-0.612**	-0.308
$C_{L/Fines}$	-0.038	-0.132	-0.521**
C_T	-0.162	-0.613**	-0.249
$C_{T/Fines}$	-0.057	-0.353	-0.533**
	Beltsville		
C_L	0.252	-0.533	0.190
C_T	0.292	-0.469	-0.001
	Keedysville		
C_L [1]	0.212	-0.415	-0.831*
C_T	0.268	-0.383	-0.840**
	Holtwood		
C_L	-0.803*	-0.826*	0.093
C_T	-0.869**	-0.729*	0.268

*, **,*** Correlation is significant at $P < 0.05$ and $P < 0.01$, $P < 0.001$ respectively.

† Relative responses were related to soil C parameters across all sites and across Piedmont sites.

CHAPTER FOUR

Effects of rye cover crops on soil quality indicators and crop productivity.

INTRODUCTION

Winter cover crops are grown when seasonal limitations prohibit production of commercial crops. The primary reason for planting cover crops has long been the prevention of erosion by cover crop interception of rainfall before it can detach soil particles (Reeves, 1994). Cover crops also reduce nutrient pollution by minimizing sediment runoff and by scavenging highly mobile residual NO_3^- when fields would normally be in fallow and subject to leaching (Lal, 1997; Staver and Brinsfield, 1998).

From a soil quality perspective, cover crops can be used to increase cropping intensity in agricultural systems thus leaving more plant residues on the soil surface and ultimately increasing soil organic carbon (SOC) levels (Dick and Gregorich, 2004). High biomass winter cover crops, such as winter rye (*Secale cereal* L.) and annual ryegrass (*Lolium multiflorum* Lam.) provide substantial C inputs to soil because of the above- and belowground residues they produce (Kuo et al., 1997). Kuo et al. (1997) estimated rye dry biomass to be 4.4 Mg ha^{-1} aboveground and 5 Mg ha^{-1} belowground to a depth of 20 cm when the crop was killed at Feekes growth stage 8 (Large, 1954). Over 6 years Kuo et al., (1997) saw a small, but detectable, increase (0.5-1.0 g kg^{-1}) in total SOC on plots where winter rye was incorporated with rototillers. In a six-year study, Wagger et al. (1998) also observed increased total SOC associated with winter rye cover crops in the temperate humid region of Washington. Sainju et al. (2000) researched conventionally

tilled soils that had high C mineralization rates and found rye cover crop use helped maintain total SOC levels.

While the importance of aboveground biomass has been discussed in the literature (Kuo et al., 1997, Dabney et al., 2001) root derived C is increasingly becoming recognized as a major source of the positive SOC building effects of high residue cover crops (Gale and Cambardella, 2000; Puget and Drinkwater, 2001). Aside from Kuo et al. (1997), discussed above, very little information is available on below-ground biomass of cover crops. Using a minirhizotron to enable root counts from 1-50 cm, Sainju et al. (1998) found rye to have higher root densities than hairy vetch(*Vicia villosa* Roth.), and crimson clover (*Trifolium incarnatum* L.). This root biomass is particularly important in no-till systems where C mineralization takes place at a slower rate allowing more root derived SOC to be protected (Gale and Cambardella, 2000). Puget and Drinkwater (2001) tracked ^{13}C labeled hairy vetch roots and found that after one growing season nearly 50% of the root derived C (compared to 13% of shoot derived C) was still present in the soil. They observed that much of the root derived C was associated with the POM fraction.

The positive influence of rye or other cereal winter cover crops has been observed in microbial biomass C (Hu et al., 1997; Mendes et al., 1999; Ndiaye et al., 2000), mineralizable C (Mendes et al., 1999; Sainju et al., 2000), mineralizable N (Mendes et al., 1999), particulate organic matter (Hu et al., 1997), soil enzymes (Ndiaye et al., 2000) and aggregate stability (Hermawan and Bomke, 1997; Gruver, 1999).

The use of cover crops to enhance soil productivity has recently been regaining acceptance (Hu et al., 1997), but this concept is not new. Odland and Knoblauch (1938)

observed increased yields in both corn (*Zea mays* L.) stover and grain when fields were treated with rye or leguminous cover crops. Studies reporting yield effects in crops grown after winter cover crops generally deal with N inputs from leguminous cover crops (Odland and Knoblauch, 1938; Smith et al., 1987; Blevins et al., 1990; Sainju et al., 2000; N'Dayegamiye and Tran, 2001; Sainju et al., 2001; others). Cash crop yield effects related to C inputs from cover crops are scarcely covered in the available literature. Current information on effects of rye cover crops on yields of subsequent cash crops is inconclusive. Odland and Knoblauch (1938) attributed yield increases to increased water holding capacity in rye treated fields. Kabir and Koide (2002) attributed higher yields of sweet corn on rye treated plots (compared to winter fallow) to enhanced P uptake in corn as a result of increased mycorrhizal activity. Bauer and Busscher (1996) compared cotton production in rye treated fields to that in fields left fallow and observed higher cotton lint yields following rye. McCracken et al. (1989) did not see significant yield effects in crops that followed rye. Eckert (1988) reported that rye mulch on fields reduced crop yields by inhibiting crop emergence. Yield reductions due to possible allelopathic effects of rye have also been reported (Raimbault et al., 1990; Kessavalou and Walters, 1997).

The objective of this study was to determine the effects of one or more years of winter rye cover crop on summer crop productivity and soil quality indicators including C mineralized in two days ($C_{min\text{-}2d}$), mineralizable N (N_{min}), percent water stable soil aggregates (WSA), $KMnO_4$ labile soil C (C_L), and total soil C (C_T).

MATERIALS AND METHODS

This study utilized the four research sites described in the Materials and Methods section in Chapter 2 of this thesis. Full descriptions of experiment layout and cropping practices and cover crop and cash crop harvest methods are given in Chapter 2. Rye root and shoot biomass data is give in Chapter 2, Table 2.5. In this study, two cover crop treatments (rye cover crop or no cover crop) were compared in eight field experiments.

Soil collection and processing procedures are given in the Materials and Methods sections of Chapter 2 and Chapter 3. Initial samples were taken in Oct. 2001 at Holtwood and in Jan. 2002 at Keedysville, Upper Marlboro, and Beltsville. Subsequent samples were taken in Aug. 2002, Aug. 2003, and Nov. 2003 at all sites. In spring 2003 the rye cover crop treatments at Upper Marlboro failed (Chapter 2, Figure 2.2). As a result Upper Marlboro data was excluded from all analyses conducted on soils and crops collected in 2003. Total soil C was analyzed on the initial soil samples and the samples from Nov. 2003. Labile soil C was analyzed on initial soil samples and on the samples taken in Aug. 2002 and Aug. 2003. Initial C_T and C_L values are given in Chapter 2, Table 2.10. Mineralizable C (in 2 days) and N_{min} (after 16 days of aerobic incubation) were analyzed on the samples taken in Aug. 2003. Percent water stable aggregates were analyzed in the Nov. 2003 samples. Methods for C_T and C_L are given in the Materials and Methods section in Chapter 2. Methods for $C_{min\text{-}2d}$, N_{min} and WSA are discussed in the Materials and Methods section of Chapter 3.

At each of eight field sites, the experimental design was a Randomized Complete Block replicated four times (see Chapter 2, Figure 2.1 for a typical plot layouts for two of these experiments). For each experiment the ANOVA model used was:

$$D.V. = COVER + BLOCK$$

where D.V. is the dependent variable being analyzed (eg. stover, grain, biomass, WSA, etc.), COVER is the cover crop treatment and BLOCK represents the blocks within each experiment. For evaluating the overall mean effects across all experiments, the ANOVA model used was:

$$D.V. = EXPERIMENT + COVER + BLOCK(EXPERIMENT)$$

where D.V. is the dependent variable being analyzed (eg. stover, grain, biomass, WSA, etc.), EXPERIMENT represents variability due to different individual experiments, COVER is the cover crop treatment and BLOCK(EXPERIMENT) represents the blocks nested within each experiment. Statistics for this study were conducted using SYSTAT version 10 (SYSTAT Software Inc., Point Richmond, CA).

RESULTS AND DISCUSSION

By ANOVA on the 2002 cash crop yields, it was observed that in two out of six experiments with one year of cover crop treatment, corn stover was greater in plots treated with rye ($COVER_{rye}$) than in plots left bare over winter ($COVER_{bare}$) (Table 4.1). The same experiments also had significantly greater total biomass in $COVER_{rye}$ plots (Table 4.1). There were no significant differences in grain yields between $COVER_{rye}$ and $COVER_{bare}$ plots observed in any of the six experiments.

Experiments 7 and 8 had received COVER since 1998. In 2002 these experiments produced soybeans (*Glycine max* M.). There were no significant differences due to rye observed in grain, stover, or biomass in these experiments (Table 4.1).

In 2003, ANOVAs for the six individual experiments where cover crop treatments were successfully applied, showed significant and positive COVER effect on soybean stover, grain and total biomass only in experiment 3 (Table 4.2). Experiment 7 had greater corn stover and total biomass in $COVER_{rye}$ plots over $COVER_{bare}$ plots (Table 4.2). No other significant effects were seen in individual experiments.

Soil C parameters for individual experiments are given in Table 4.3. There were no significant differences seen in Aug. 2002 C_L after at least one year of COVER. Experiment 7, which had received COVER for five years, showed significantly greater C_L (in Aug. 2003 soil samples) in $COVER_{rye}$ plots. In experiments 3 and 7, $C_{min\text{-}2d}$ (Aug. 2003 samples) was significantly greater in $COVER_{rye}$ plots compared to $COVER_{bare}$ plots.

ANOVA of N_{min} (Aug. 2003 samples) in individual experiments revealed significantly greater N_{min} in $COVER_{rye}$ plots in three out of six experiments (Table 4.4). WSA was significantly greater in $COVER_{rye}$ in experiment 3.

Analysis of overall effects of one year of COVER on 2002 corn yields across experiments 1 – 6 showed significantly greater corn stover and total biomass in $COVER_{rye}$ plots (Table 4.5). Analysis of the overall effects of COVER on soybean yields in 2002 in experiments 7 and 8 along with the soybean yields in 2003 in experiments 1 – 4 showed that after two or more years of cover crop treatment, soybean stover, grain and biomass was significantly higher in $COVER_{rye}$ plots (Table 4.5).

The effect of COVER on C_L measured in Aug. 2002 was not significant when analyzed across all experiments. After at least two years of COVER there was significantly greater C_L (Aug. 2003 samples), $C_{min\text{-}2d}$, N_{min}, and WSA in $COVER_{rye}$ plots

when analyzed across experiments 1, 2, 3, 4, 7 and 8 (Table 4.5). Analysis of the overall effect of COVER on C_T in Nov. 2003 samples across these same experiments did not reveal any significant differences.

It is of note that after at least two years of COVER C_L, $C_{min\text{-}2d}$, N_{min}, and WSA all show significant differences in the overall effects of COVER, while C_T does not. The parameters that show sensitivity to COVER are all associated with the active pool of soil organic matter (SOM). This supports the concept that measurements representative of the active pool are more sensitive to soil management practices than the more recalcitrant materials comprising C_T (Biederbeck et al., 1994; Gregorich et al., 1994; Magdoff, 1996; Islam and Weil, 2000; Weil and Magdoff, 2004; others).

The improved crop productivity may be a result partly from higher levels of N_{min} in rye treated plots. In addition the greater overall WSA in rye treated plots, combined with the decaying rye mulch that is left on the soil surface, may enhance soil water holding capabilities in rye treated plots which could affect crop yields.

CONCLUSIONS

This study has shown that crop productivity and soil quality can be positively impacted in no-till systems through the use of rye as a winter cover crop in the Mid-Atlantic region of the eastern U.S. Effects on crop productivity were greater in stover and total biomass rather than grain, which is more subject to transient environmental stressors. Across eight field experiments, soil quality indicator properties related to the active pool of SOM, including C_L, $C_{min\text{-}2d}$, N_{min}, and WSA, were enhanced by the rye cover crop. The effects were more pronounced after more than one year of cover crop

treatment. This is in agreement with previous research that suggests that rye cover crops can increase soil C parameters, improve soil structure, and enhance crop productivity.

REFERENCES

Bauer, P.J., and W.J. Busscher, 1996. Winter cover and tillage influences on Coastal Plain cotton production. J. Product. Agric. 9:50-54.

Biederbeck, V.O., H.H. Janzen, C.A. Campbell, R.P. Zentner. 1994. Labile soil organic matter as influenced by cropping practices in an arid environment. Soil Biol. Biochem. 26:1647-1656.

Blevins, R.L., J.H. Herbeck, and W.W. Frye. 1990. Legume cover crops as a nitrogen source for no-till corn and grain sorghum. Agron. J. 82:769-772.

Dabney, S.M., J.A. Delgado, and D.W. Reeves. 2001. Using winter cover crops to improve soil and water quality. Commun. Soil Sci. Plant Anal. 32:1221–1250.

Dick, W.A., and E.G. Gregorich. 2004. Developing and maintaining soil organic matter levels. p. 103-120. In P. Schjonning, S. Elmholt, and B.T. Christensen (ed.) Managing Soil Quality: Challenges in modern agiculture. CABI Publishing, Oxon, United Kingdom.

Eckert, D.J. 1988. Rye cover crops for no-tillage corn and soybean production. J. Prod. Agric. 1:207-210.

Gale, W.J. and C.A. Cambardella. 2000. Carbon dynamics of surface residue- and root-derived organic matter under simulated no-till. Soil Sci. Soc. Am. J. 64:190-195.

Gregorich, E.G., M.R. Carter, D.A. Angers, C.M. Monreal, and B.H. Ellert. 1994. Towards a minimum data set to assess soil organic matter quality in agricultural soils. Can. J. Soil Sci. 74:367-385.

Gruver, J.B. 1999. Relationships between farmer perceptions of soil quality and management sensitive soil parameters. M.S. Thesis. University of Maryland, Colllege Park, MD.

Hermawan, B., and A.A. Bomke. 1997. Effects of winter cover crops and successive spring tillage on soil aggregation. Soil Tillage Res. 44:109-120.

Hu, S., N.J. Grunwald, A.H.C. van Bruggen, G.R. Gamble, L.E. Drinkwater, C Shennan, and M.W. Demment. 1997. Short-term effects of cover crop incorporation on soil carbon pools and nitrgen availability. Soil Sci. Soc. Am. J. 61:901-911.

Islam, K.R. and R.R. Weil. 2000. Soil quality indicator properties in mid-Atlantic soils as influenced by conservation management. J. Soil Water Conserv. 55:69-78.

Kabir, Z. and R.T. Koide. 2002. Effect of autumn and winter mycorerhizal cover crops on soil properties, nutrient uptake and yield of sweet corn in Pensylvania, USA. Plant Soil 238:205-215.

Kessavalou, A., and D.T. Walters. 1997. Winter rye as a cover crop following soybean under conservation tillage. Agron. J. 89:68-74.

Kuo, S., Sainju, U.M., and E.J. Jellum. 1997. Winter cover crop efects on soil organic carbon and carbohydrate in soil. Soil Sci. Soc. Am. J. 61:145-152.

Lal, R. 1997. Land use and soil management effects on soil organic matter dynamicson Alfisols in Western Nigeria. In: R Lal, J.M. Kimble, R.F. Follett, and B.A. Stewart. (eds.) Soil processes and the carbon cycle. CRC Press, Boca Raton, Fl.

Large, E.C. 1954. Growth stages in cereals. Illustration of the Feekes scale. Plant Pathol. 3:128-129.

Magdoff, F. 1996. Soil organic matter fractions and implications for interpreting soil organic matter tests. p. 11-19. In F.R. Magdoff, M.A. Tabatabai, and E.A. Hanlon, Jr. (ed.) Soil organic matter: Analysis and interpretation. SSSA Spec. Publ. 46. SSSA, Madison, WI.

McCracken, D.V., S.J. Corak, M.S. Smith, W.W. Frye, and R.L.Blevins. 1989. Residual effects of nitrogen fertilization and winter cover cropping on nitrogen availability. Soil Sci. Soc. Am. J. 53:1459-1464.

Mendes, I.C., A.K. Bandick, R.P. Dick, and P.J. Bottomley. 1999. Microbial biomass and activities in soil aggregates affected by winter cover crops. Soil Sci. Soc. Am. J. 63:873-881.

N'Dayegamiye, A., and T.S. Tran. 2001. Effects of green manures on soil organic matter and wheat yields and N nutrition. Can. J. Soil Sci. 81:371-382.

Ndiaye, E.L., Sandeno, J.M., McGrath, D. and R.P. Dick. 2000. Integrative biological indicators for detecting change in soil quality. Am. J. Alt. Agric. 15:26-36.

Odland, T.E., and H.C. Knoblauch. 1938. The value of cover crops in continuous corn culture. J. Am. Soc. Agron. 30:22-29.

Puget, P. and L.E. Drinkwater. 2001. Short-term dynamics of root and shoot derived carbon from a leguminous green manure. Soil Sci. Soc. Am. J. 65:771-779.

Raimbault, B.A., T.J. Vyn, and M. Tollenaar. 1990. Corn Response to rye cover crop management and spring tillage systems. Agron. J. 82:1088-1093.

Reeves, D. W. 1994. Cover crops and rotations. pp.125–172. In: J.L. Hatfield and B.A. Stewart (eds.) Crops Residue Management. Advances in Soil Science. Lewis Publishers, Boca Raton, FL.

Sainju, U.M., B.P. Singh, and W.F. Whitehead. 1998. Cover crop root distribution and its effects on soil nitrogen cycling. Agron. J. 90:511-518.

Sainju, U.M., B.P. Singh, and W.F. Whitehead. 2000. Cover crops and nitrogen fertilization effects on soil carbon and nitrogen and tomato yield. Can. J. Soil Sci. 80:523-532.

Sainju, U.M., B.P. Singh, and W.F. Whitehead. 2001. Comparison of the effects of cover crops and nitrogen fertilization on tomato yield, root growth and soil properties. Scientia Horticulturae 91:2001-214.

Smith, M.S., W.W. Frye, and J.J. Varco. 1987. Legume winter cover crops. Adv Soil Sci. 7:95-139.

Staver, K.W. and R.B. Brinsfield. 1998. Using cereal grain winter cover crops to reduce groundwater nitrate contamination in the mid-Atlantic coastal plains. J. Soil Water Cons. 53:230 –240.

Wagger, M.G., M.L. Cabrera, and N.N. Rannels. 1998. Nitrogen and carbon cycling in relation to cover crop residue quality. Soil Water Cons. 53:214-224.

Weil, R.R., and F. Magdoff. 2004. Significance of soil organic matter to soil quality and health. p. 1-43. In F. Magdoff and R.R. Weil (ed.) Soil organic matter in sustainable agriculture. CRC Press. Boca Raton, FL.

FIGURES AND TABLES

Table 4.1. The effects of at least one year of winter cover crop treatments in eight experiments on cash crop stover, grain and total biomass production in 2002.

		Cover Crop Treatment					
		No Rye	Rye	No Rye	Rye	No Rye	Rye
Experiment	Site	Stover		Grain		Total Biomass	
		kg ha^{-1}		kg ha^{-1}		kg ha^{-1}	
1	Beltsville	4858.7	5105.3	6179.0	6709.2	10764.7	11814.5
2	Beltsville	6529.6	5737.7	5006.2	7510.9	11535.8	13248.6
3	Keedysville	4879.6 **	8423.7	8630.1	8853.4	13509.7 *	17277.1
4	Keedysville	6262.6	8044.6	7151.1	7660.9	13413.7	15705.4
5	Upper Marlboro	5887.8	6763.9	5525.9	5439.9	11413.7	12203.8
6	Upper Marlboro	4704.1 *	7343.6	4454.0	4028.2	9158.1 *	11371.8
7†‡	Holtwood	8878.1	10188.3	3922.8	4675.7	12800.9	14864.0
8†‡	Holtwood	7265.2	7868.3	3113.4	3273.2	10378.6	11141.5

*, **: Adjacent means are significantly different at $P < 0.05$ and $P < 0.01$, respectively.

†: Soybeans were produced in experiments 7 and 8 while corn was produced in all other experiments in 2002.

‡: The cover crop treatments on these experiments had been in place since 1998. All other experiments had one year of treatment.

Table 4.2. The effects of two or more years of winter cover crop treatments in eight experiments on cash crop stover, grain and total biomass production in 2003.

		Cover Crop Treatment								
		No Rye		Rye	No Rye		Rye	No Rye		Rye
Experiment	Site	Stover			Grain			Biomass		
		kg ha^{-1}			kg ha^{-1}			kg ha^{-1}		
1	Beltsville	2965.3		3897.9	1613.0		2080.1	4578.4		5978.0
2	Beltsville	4918.5		4791.3	2809.5		2635.8	7728.0		7427.1
3	Keedysville	4511.6	**	5770.9	2804.7	*	3555.1	7316.2	**	9326.0
4	Keedysville	3114.2		3453.9	1965.3		2109.5	5079.6		5563.4
7‡	Holtwood	5049.5	*	6284.2	9314.4		10716.5	14408.9	*	17000.7
8‡	Holtwood	5410.7		4956.7	9132.6		9606.7	14543.3		14563.4

*, **: Adjacent means are significantly different at $P < 0.05$ and $P < 0.01$, respectively.

†: Corn was produced in experiments 7 and 8 while soybeans were produced in all other experiments in 2003.

‡: The cover crop treatments on these experiments had been in place since 1998. All other experiments had two years of treatment.

Table 4.3. The effects winter cover crop treatments in eight experiments on soil C parameters.

		Cover Crop Treatment											
		No Rye	Rye	No Rye	Rye	No Rye		Rye		No Rye	Rye		
Experiment	Site	Aug 2002 C_L†		Aug 2003 C_L‡		C_{min}‡				C_T‡			
		mg kg^{-1}		mg kg^{-1}		mg kg^{-1}				g kg^{-1}			
1	Beltsville	536.8	542.2	394.8	457.7	71.28		77.54		9.42	10.01		
2	Beltsville	700.4	741.7	641.1	617.7	137.38		154.87		16.17	16.15		
3	Keedysville	437.6	452.0	443.0	509.6	185.39	*	228.83		12.83	15.69		
4	Keedysville	878.4	822.6	754.3	775.8	368.18		441.55		22.57	22.02		
5	Upper Marlboro	357.1	367.9	N/A	N/A	N/A		N/A		N/A	N/A		
6	Upper Marlboro	748.9	757.9	N/A	N/A	N/A		N/A		N/A	N/A		
7§	Holtwood	658.9	711.1	675.1	* 770.4	244.91	**	346.93		19.00	20.50		
8§	Holtwood	793.8	829.8	837.0	838.8	271.31		280.27		27.39	30.00		

*, **: Adjacent means are significantly different at $P < 0.05$ and $P < 0.01$, respectively.

†: One (Experiments 1-6) or more (Experiments 7 & 8) winter cover crop treatments.

‡: Two (Experiments 1-6) or more (Experiments 7 & 8) winter cover crop treatments.

§: The cover crop treatments on these experiments had been in place since 1998. Cover crop treatments in all other experiments were initiated in autumn 2001.

Table 4.4. The effects winter cover crop treatments in six experiments on mineralizable N and percent water stable aggregates.

Experiment	Site	Cover Crop Treatment					
		No Rye		Rye	No Rye		Rye
		N_{min}			WSA		
		mg kg^{-1}			%		
1	Beltsville	24.21	*	42.37	66.16		66.13
2	Beltsville	29.20		31.85	79.01		82.76
3	Keedysville	65.79	*	105.17	15.36	*	36.11
4	Keedysville	84.18		104.35	85.50		86.50
7‡	Holtwood	138.50	*	179.69	48.49		59.56
8‡	Holtwood	150.19		147.34	97.85		85.34

*: Adjacent means are significantly different at $P < 0.05$.

†: Two (Experiments 1-4) or more (Experiments 7 & 8) winter cover crop treatments.

‡: The cover crop treatments on these experiments had been in place since 1998. Cover crop treatments in all other experiments were initiated in autumn 2001.

Table 4.5. Effects of one year and more than one year of winter cover crop treatments on crop productivity and soil quality parameters averaged across six experiments.

	Cover Crop Treatment		
Crop or Soil Parameter	No Rye		Rye
	One Year		
Stover† kg ha^{-1}	5474.9	**	6903.1
Grain† kg ha^{-1}	6157.7		6700.4
Biomass† kg ha^{-1}	11632.6	**	13603.5
C_L mg kg^{-1}	639.0		653.2
	More than One Year		
Stover‡ kg ha^{-1}	5275.5	**	5995.1
Grain‡ kg ha^{-1}	2704.8	*	3054.9
Biomass‡ kg ha^{-1}	7890.3	**	9050.0
C_L mg kg^{-1}	624.2	**	661.7
$C_{min\text{-}2d}$ mg kg^{-1}	213.1	**	255.0
C_T g kg^{-1}	17.90		19.06
N_{min} mg kg^{-1}	82.01	**	101.81
WSA %	60.40	**	69.40

†: Overall effects on crop parameters were tested across experiments 1-6, which produced corn in 2002.

‡: Overall effects on crop parameters were tested across experiments 1-4 using the soybean yields from 2003 (this table) and the analysis also included experiments 7 and 8 which produced soybeans in 2002 (Table 4.1). Experiments 7 and 8 received the cover crop treatments since 1998.

APPENDICES

Appendix A: Field soil profile descriptions at Beltsville. Keedysville, Upper Marlboro, and Holtwood. Locations in column 1 can be found *in italics* on layout maps in Appendix B. As decriptions were performed prior to plot layout over a larger area than the final plot layout, some locations are not shown. These descriptions were taken in a location that was beyond the borders of the final plots. The symbol "--" indicates that the feature was not present. The symbol "N/A" means that description was not attempted.

Beltsville

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
A	0-5	10YR3/4	--	--	ls	5	--
A	5-15	10YR3/6	--	--	ls	5	--
A	15-25	10YR5/4	--	--	ls	5	--
A	25-35	10YR6/8	--	--	ls	5	--
A	35-45	10YR6/8	--	--	ls	5	--
A	45-55	10YR6/8			ls	5	Many Rocks
A	55-65	N/A	N/A	N/A	N/A	N/A	N/A
A	65-75	N/A	N/A	N/A	N/A	N/A	N/A
A	75-85	N/A	N/A	N/A	N/A	N/A	N/A
A	85-95	N/A	N/A	N/A	N/A	N/A	N/A

Beltsville

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
B	0-5	10YR3/4	--	--	ls	5	--
B	5-15	10YR3/6	--	--	ls	5	--
B	15-25	10YR4/4	--	--	ls	5	--
B	25-35	10YR4/6	--	--	ls	4	--
B	35-45	10YR6/6	--	--	ls	4	--
B	45-55	10YR6/6	--	--	ls	4	--
B	55-65	10YR6/6	--	--	ls	6	--
B	65-75	10YR6/6	--	--	ls	6	--
B	75-85	10YR4/4	--	--	sl	12	--
B	85-95	10YR4/4	--	--	sl	15	--

Beltsville

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
C	0-5	10YR3/4	--	--	ls	5	--
C	5-15	10YR3/6	--	--	ls	5	--
C	15-25	10YR5/6	--	--	ls	5	--
C	25-35	10YR6/8	--	--	ls	5	--
C	35-45	10YR6/8	--	--	ls	5	--
C	45-55	10YR6/8	--	--	ls	5	--
C	55-65	10YR6/8	--	--	ls	5	--
C	65-75	10YR6/8	--	--	ls	5	Few Rocks
C	75-85	10YR6/8	--	--	ls	5	Few Rocks
C	85-95	10YR6/8	--	--	ls	5	Common Rocks

Beltsville

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
D	0-5	10YR3/4	--	--	ls	5	--
D	5-15	10YR3/6	--	--	ls	5	--
D	15-25	10YR6/8	--	--	ls	5	--
D	25-35	10YR6/8	--	--	ls	5	--
D	35-45	10YR6/8	--	--	ls	5	--
D	45-55	10YR6/8	--	--	ls	5	--
D	55-65	10YR6/8	--	--	ls	5	Few Rocks
D	65-75	10YR6/8	--	--	s	2	Few Rocks
D	75-85	10YR7/8	--	--	s	2	Few Rocks
D	85-95	10YR7/8	--	--	s	2	Many Rocks

Beltsville

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
E	0-5	10YR3/4	--	--	ls	5	--
E	5-15	10YR3/6	--	--	ls	5	--
E	15-25	10YR4/6	--	--	ls	5	--
E	25-35	10YR6/6	--	--	ls	5	--
E	35-45	10YR6/6	--	--	ls	5	--
E	45-55	10YR6/6	--	--	ls	8	Few Rocks
E	55-65	10YR5/8	--	--	ls	10	--
E	65-75	10YR5/8	--	--	ls	10	--
E	75-85	7.5YR5/8	--	--	ls	5	Many Rocks
E	85-95	N/A	N/A	N/A	N/A	N/A	N/A

Beltsville

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
F	0-5	10YR3/4	--	--	ls	5	--
F	5-15	10YR3/6	--	--	ls	5	--
F	15-25	10YR5/6	--	--	ls	5	--
F	25-35	10YR5/6	--	--	ls	5	--
F	35-45	10YR5/6	--	--	ls	5	--
F	45-55	7.5YR4/6	--	--	scl	25	--
F	55-65	7.5YR4/6	--	--	scl	25	--
F	65-75	7.5YR5/6	--	--	ls	15	--
F	75-85	7.5YR6/8	--	--	s	2	Many Rocks
F	85-95	N/A	N/A	N/A	N/A	N/A	N/A

Beltsville

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
G	0-5	10YR3/3	--	--	ls	5	--
G	5-15	10YR5/3	--	--	ls	5	--
G	15-25	10YR6/3	--	--	ls	5	--
G	25-35	10YR6/3	--	--	ls	5	--
G	35-45	10YR6/3	--	--	ls	5	Few Rocks
G	45-55	10YR6/3	--	--	ls	5	--
G	55-65	10YR6/3	N/A	N/A	sl	12	Weak Redox
G	65-75	10YR7/4	N/A	N/A	sl	12	Weak Redox
G	75-85	10YR7/4	N/A	N/A	sl	12	Weak Redox, Common Rocks
G	85-95	10YR7/4	N/A	N/A	sl	20	Strong Redox

Beltsville

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
H	0-5	10YR3/3	--	--	ls	5	--
H	5-15	10YR5/3	--	--	ls	5	--
H	15-25	10YR6/3	--	--	ls	5	--
H	25-35	10YR6/3	--	--	ls	5	--
H	35-45	10YR6/3	--	--	ls	5	Few Rocks
H	45-55	10YR6/3	--	--	ls	8	--
H	55-65	10YR6/3	N/A	N/A	sl	12	Weak Redox
H	65-75	10YR6/3	N/A	N/A	scl	25	Weak Redox
H	75-85	10YR6/3	N/A	N/A	scl	25	Strong Redox
H	85-95	10YR8/2	N/A	N/A	cl	30	Strong Redox

Beltsville

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
I	0-5	10YR3/3	--	--	ls	5	--
I	5-15	10YR5/3	--	--	ls	5	--
I	15-25	10YR6/8	--	--	ls	5	--
I	25-35	10YR6/8	--	--	ls	5	--
I	35-45	10YR6/8	--	--	ls	5	--
I	45-55	10YR6/8	--	--	ls	5	--
I	55-65	10YR6/8	N/A	N/A	ls	8	Weak Redox
I	65-75	10YR6/8	N/A	N/A	ls	5	Weak Redox
I	75-85	10YR6/8	N/A	N/A	ls	5	Weak Redox
I	85-95	10YR8/2	N/A	N/A	s	2	Strong Redox

Beltsville

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
J	0-5	10YR3/3	--	--	ls	5	--
J	5-15	10YR5/3	--	--	ls	5	--
J	15-25	10YR7/6	--	--	ls	5	--
J	25-35	10YR7/6	--	--	ls	5	Common Rocks
J	35-45	10YR7/6	--	--	ls	5	Common Rocks
J	45-55	10YR7/6	--	--	ls	5	Common Rocks
J	55-65	10YR7/6	--	--	ls	5	Common Rocks
J	65-75	10YR7/6	--	--	ls	5	--
J	75-85	10YR7/6	--	--	ls	5	--
J	85-95	10YR5/8	--	--	sl	12	--

Beltsville

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
K	0-5	10YR3/3	--	--	ls	5	--
K	5-15	10YR5/3	--	--	ls	5	--
K	15-25	10YR5/6	--	--	ls	5	--
K	25-35	10YR6/8	--	--	ls	5	--
K	35-45	10YR6/8	--	--	ls	5	--
K	45-55	10YR6/8	--	--	ls	5	--
K	55-65	10YR6/8	--	--	ls	5	--
K	65-75	10YR6/8	--	--	ls	5	--
K	75-85	10YR6/8	N/A	N/A	sl	12	Weak Redox
K	85-95	10YR6/8	N/A	N/A	sl	18	Weak Redox

Beltsville

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
L	0-5	10YR3/3	--	--	ls	5	--
L	5-15	10YR5/3	--	--	ls	5	--
L	15-25	10YR5/6	--	--	ls	5	--
L	25-35	10YR6/8	--	--	ls	5	--
L	35-45	10YR6/8	--	--	ls	5	--
L	45-55	10YR6/8	--	--	ls	5	--
L	55-65	10YR6/8	--	--	ls	5	--
L	65-75	10YR6/8	--	--	ls	5	--
L	75-85	10YR6/8	N/A	N/A	sl	12	Weak Redox
L	85-95	10YR5/8	N/A	N/A	ls	5	Weak Redox, Few Rocks

Keedysville

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
A	0-5	7.5YR4/6	--	--	sil	12	--
A	5-15	7.5YR4/6	--	--	sil	12	--
A	15-25	7.5YR5/8	--	--	sil	15	--
A	25-35	7.5YR5/8	--	--	sil	15	--
A	35-45	7.5YR5/8	--	--	sil	25	--
A	45-55	7.5YR5/8	--	7.5YR8/6	sicl	40	Weak Redox
A	55-65	7.5YR5/8	--	7.5YR8/6	sicl	40	Weak Redox
A	65-75	7.5YR5/8	--	7.5YR8/6	sicl	40	Weak Redox
A	75-85	7.5YR5/8	--	7.5YR8/6	sicl	30	Weak Redox
A	85-95	7.5YR5/8	--	7.5YR8/6	sicl	30	Weak Redox

Keedysville

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
B	0-5	7.5YR4/6	--	--	sil	12	--
B	5-15	7.5YR4/6	--	--	sil	12	--
B	15-25	7.5YR5/8	--	--	sil	22	--
B	25-35	7.5YR5/8	--	--	sil	20	--
B	35-45	7.5YR5/8	--	--	sicl	35	Many Rocks
B	45-55	N/A	N/A	N/A	N/A	N/A	N/A
B	55-65	N/A	N/A	N/A	N/A	N/A	N/A
B	65-75	N/A	N/A	N/A	N/A	N/A	N/A
B	75-85	N/A	N/A	N/A	N/A	N/A	N/A
B	85-95	N/A	N/A	N/A	N/A	N/A	N/A

Keedysville

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
C	0-5	7.5YR4/6	--	--	sil	12	--
C	5-15	7.5YR4/6	--	--	sil	12	--
C	15-25	7.5YR4/6	--	--	sil	12	--
C	25-35	7.5YR5/8	--	--	sil	12	--
C	35-45	7.5YR5/8	--	--	sil	12	--
C	45-55	7.5YR5/8	--	--	sil	12	--
C	55-65	7.5YR5/6	--	--	sil	12	--
C	65-75	7.5YR5/6	--	7.5YR8/6	sil	12	Weak Redox
C	75-85	7.5YR5/6	--	7.5YR8/6	sil	12	Weak Redox
C	85-95	7.5YR5/6	--	7.5YR8/6	sil	25	Weak Redox

Keedysville

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
D	0-5	7.5YR4/6	--	--	sil	12	--
D	5-15	7.5YR4/6	--	--	sil	12	--
D	15-25	7.5YR4/6	--	--	sil	12	--
D	25-35	7.5YR4/6	--	--	sil	12	--
D	35-45	7.5YR4/6	--	--	sil	10	--
D	45-55	7.5YR5/8	--	7.5YR8/6	sil	15	Weak Redox
D	55-65	7.5YR5/8	--	7.5YR8/6	sicl	35	Weak Redox
D	65-75	7.5YR5/8	--	7.5YR8/6	sicl	40	Weak Redox
D	75-85	7.5YR5/8	--	7.5YR8/6	sil	25	Weak Redox
D	85-95	7.5YR5/8	--	7.5YR8/6	sil	25	Weak Redox

Keedysville

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
E	0-5	7.5YR4/6	--	--	sil	12	--
E	5-15	7.5YR4/6	--	--	sil	12	--
E	15-25	7.5YR5/8	--	--	sil	15	--
E	25-35	7.5YR5/8	--	--	sicl	30	--
E	35-45	7.5YR5/8	--	--	sicl	40	--
E	45-55	7.5YR5/8	--	--	sicl	40	--
E	55-65	7.5YR5/8	--	7.5YR7/8	sicl	40	Weak Redox
E	65-75	7.5YR5/8	--	7.5YR7/8	sicl	40	Weak Redox
E	75-85	7.5YR5/8	--	7.5YR7/8	sicl	40	Strong Redox
E	85-95	7.5YR5/8	--	7.5YR7/8	sicl	40	Strong Redox

Keedysville

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
F	0-5	7.5YR4/6	--	--	sil	12	--
F	5-15	7.5YR5/6	--	--	sil	12	--
F	15-25	7.5YR5/6	--	--	sil	15	--
F	25-35	7.5YR5/6	--	--	sicl	30	Many Rocks
F	35-45	N/A	N/A	N/A	N/A	N/A	N/A
F	45-55	N/A	N/A	N/A	N/A	N/A	N/A
F	55-65	N/A	N/A	N/A	N/A	N/A	N/A
F	65-75	N/A	N/A	N/A	N/A	N/A	N/A
F	75-85	N/A	N/A	N/A	N/A	N/A	N/A
F	85-95	N/A	N/A	N/A	N/A	N/A	N/A

Keedysville

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
G	0-5	7.5YR3/4	--	--	sil	12	--
G	5-15	7.5YR3/4	--	--	sil	12	--
G	15-25	7.5YR5/8	--	--	sicl	35	--
G	25-35	7.5YR5/8	--	7.5YR8/6	sicl	35	Weak Redox
G	35-45	7.5YR5/8	--	7.5YR8/6	sicl	35	Weak Redox
G	45-55	7.5YR5/8	--	7.5YR8/6	sicl	35	Weak Redox
G	55-65	7.5YR5/8	--	7.5YR8/6	sicl	35	Weak Redox
G	65-75	7.5YR5/8	--	7.5YR8/6	sicl	21	Weak Redox
G	75-85	7.5YR5/8	--	7.5YR8/6	sil	18	Weak Redox
G	85-95	7.5YR5/8	--	7.5YR8/6	sil	18	Weak Redox

Keedysville

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
H	0-5	7.5YR3/4	--	--	sil	12	--
H	5-15	7.5YR3/4	--	--	sil	12	--
H	15-25	7.5YR4/6	--	--	sil	15	--
H	25-35	7.5YR6/8	--	--	sil	18	--
H	35-45	7.5YR6/8	--	--	sicl	21	--
H	45-55	7.5YR6/8	--	--	sicl	27	--
H	55-65	7.5YR5/8	--	7.5YR8/6	sicl	30	Weak Redox
H	65-75	7.5YR5/8	--	7.5YR8/6	sicl	35	Weak Redox
H	75-85	7.5YR6/8	--	7.5YR8/6	sicl	35	Weak Redox
H	85-95	7.5YR6/8	--	7.5YR8/6	sicl	25	Weak Redox

Keedysville

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
I	0-5	7.5YR3/4	--	--	sil	12	--
I	5-15	7.5YR3/4	--	--	sil	12	--
I	15-25	7.5YR4/6	--	--	sil	12	--
I	25-35	7.5YR4/6	--	--	sil	12	--
I	35-45	7.5YR4/6	--	--	sil	12	--
I	45-55	7.5YR4/6	--	--	sil	12	--
I	55-65	7.5YR4/6	--	--	sil	12	--
I	65-75	7.5YR5/6	--	--	sil	12	--
I	75-85	N/A	N/A	N/A	N/A	N/A	N/A
I	85-95	N/A	N/A	N/A	N/A	N/A	N/A

Keedysville

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
J	0-5	7.5YR3/4	--	--	sil	12	--
J	5-15	7.5YR3/4	--	--	sil	12	--
J	15-25	7.5YR4/6	--	--	sil	12	--
J	25-35	7.5YR6/8	--	7.5YR8/6	sicl	30	Weak Redox
J	35-45	7.5YR5/6	--	7.5YR8/6	sil	18	Weak Redox
J	45-55	7.5YR6/8	--	7.5YR8/6	sicl	28	Weak Redox
J	55-65	7.5YR6/8	--	7.5YR8/6	sicl	28	Weak Redox
J	65-75	7.5YR6/8	--	7.5YR8/6	sicl	28	Weak Redox
J	75-85	7.5YR6/6	--	7.5YR8/6	sil	18	Weak Redox
J	85-95	7.5YR6/6	--	7.5YR8/6	sil	18	Weak Redox

Keedysville

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
K	0-5	7.5YR3/4	--	--	sil	12	--
K	5-15	7.5YR3/4	--	--	sil	12	--
K	15-25	7.5YR4/6	--	--	sil	15	--
K	25-35	7.5YR5/6	--	--	sil	15	--
K	35-45	7.5YR5/6	--	--	sil	15	--
K	45-55	7.5YR5/6	--	--	sil	18	--
K	55-65	7.5YR6/8	--	--	sil	18	--
K	65-75	7.5YR5/8	--	7.5YR8/6	sil	18	Weak Redox
K	75-85	7.5YR5/8	--	7.5YR8/6	sil	15	Weak Redox
K	85-95	7.5YR5/8	--	7.5YR8/6	sicl	22	Weak Redox

Keedysville

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
L	0-5	7.5YR3/4	--	--	sil	12	--
L	5-15	7.5YR3/4	--	--	sil	12	--
L	15-25	7.5YR4/6	--	--	sil	15	--
L	25-35	7.5YR4/6	--	--	sil	15	--
L	35-45	7.5YR4/6	--	--	sil	15	--
L	45-55	7.5YR4/6	--	--	sil	15	--
L	55-65	7.5YR6/8	--	--	sil	15	--
L	65-75	7.5YR6/8	--	--	sil	15	--
L	75-85	7.5YR6/8	--	7.5YR8/6	sil	20	Weak Redox
L	85-95	7.5YR6/8	--	7.5YR8/6	sil	18	Weak Redox

Upper Marlboro

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
A	0-5	10YR4/4	--	--	fsl	15	--
A	5-15	2.5YR4/4	--	--	fsl	15	--
A	15-25	2.5YR4/4	--	2.5YR5/2	fsl	18	Weak Redox
A	25-35	2.5YR5/4	--	2.5YR5/2	fsl	22	Weak Redox
A	35-45	2.5YR5/4	--	2.5YR5/2	fsl	22	Weak Redox
A	45-55	2.5YR5/4	7.5YR5/8	2.5YR5/2	fsl	24	Weak Redox
A	55-65	2.5YR5/4	7.5YR5/8	2.5YR5/2	fsl	25	Strong Redox
A	65-75	2.5YR5/4	7.5YR5/8	5GY5/1	fsl	25	Strong Redox
A	75-85	2.5YR5/4	7.5YR5/8	5GY5/1	fscl	30	Strong Redox
A	85-95	N/A	N/A	N/A	N/A	N/A	N/A

Upper Marlboro

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
B	0-5	2.5YR4/4	--	--	fsl	12	--
B	5-15	2.5YR4/4	--	--	fsl	12	--
B	15-25	2.5YR5/4	--	2.5YR5/2	fsl	12	Weak Redox
B	25-35	2.5YR5/4	--	2.5YR5/2	fsl	20	Weak Redox
B	35-45	2.5YR5/4	--	2.5YR5/2	fsl	20	Weak Redox
B	45-55	2.5YR5/4	7.5YR5/8	5GY5/1	fsl	15	Weak Redox
B	55-65	2.5YR5/4	--	5GY5/1	fsl	12	Weak Redox
B	65-75	2.5YR5/4	--	5GY5/1	fsl	12	Weak Redox
B	75-85	2.5YR5/4	--	5GY5/1	fls	8	Strong Redox
B	85-95	N/A	--	N/A	N/A	N/A	N/A

Upper Marlboro

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
C	0-5	2.5YR5/4	--	--	fsl	12	--
C	5-15	2.5YR5/4	--	--	fsl	12	--
C	15-25	2.5YR5/4	--	2.5YR5/2	fsl	15	Weak Redox
C	25-35	2.5YR5/4	--	2.5YR5/2	fsl	18	Weak Redox
C	35-45	2.5YR5/4	--	5GY5/1	fsl	25	Strong Redox
C	45-55	2.5YR5/4	7.5YR5/8	5GY5/1	fsl	15	Strong Redox
C	55-65	2.5YR5/4	7.5YR5/8	5GY5/1	fsl	12	Strong Redox
C	65-75	2.5YR5/4	7.5YR5/8	5GY5/1	fsl	12	Weak Redox
C	75-85	2.5YR5/4	7.5YR5/8	5GY5/1	fsl	12	Weak Redox
C	85-95	2.5YR5/4	7.5YR5/8	5GY5/1	fsl	12	Strong Redox

Upper Marlboro

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
D	0-5	2.5YR4/4	--	--	fsl	10	--
D	5-15	2.5YR4/4	--	--	fsl	10	--
D	15-25	2.5YR4/4	--	2.5YR5/2	fsl	10	Weak Redox
D	25-35	2.5YR5/4	--	5GY5/1	fsl	15	Weak Redox
D	35-45	2.5YR5/4	--	5GY5/1	fsl	17	Weak Redox
D	45-55	2.5YR5/4	--	5GY5/1	fsl	17	Weak Redox
D	55-65	2.5YR5/4	--	5GY5/1	fsl	17	Weak Redox
D	65-75	2.5YR5/4	--	5GY5/1	fsl	17	Weak Redox
D	75-85	2.5YR5/4	--	5GY5/1	fsl	10	Weak Redox
D	85-95	2.5YR5/4	--	5GY5/1	fsl	10	Weak Redox

Upper Marlboro

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
E	0-5	10YR3/4	--	10YR5/2	fsl	15	Weak Redox
E	5-15	10YR3/4	--	10YR5/2	fsl	15	Weak Redox
E	15-25	10YR5/6	--	10YR5/2	fscl	29	Strong Redox
E	25-35	10YR5/6	--	10YR5/2	fscl	32	Strong Redox
E	35-45	10YR5/6	--	10YR5/2	fscl	28	Strong Redox
E	45-55	5GY5/1	7.5YR5/8	N7	fscl	35	Strong Redox
E	55-65	5GY5/1	7.5YR5/8	N7	fscl	38	Strong Redox
E	65-75	5GY5/1	7.5YR5/8	N7	fsc	42	Strong Redox
E	75-85	5GY5/1	7.5YR5/8	N7	fsc	45	Strong Redox
E	85-95	5GY5/1	--	2.5Y5/2	fsl	15	Strong Redox

Upper Marlboro

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
F	0-5	10YR3/4	--	10YR5/2	fsl	15	--
F	5-15	10YR3/4	--	10YR5/2	fsl	15	Weak Redox
F	15-25	10YR3/4	--	10YR5/2	fscl	30	Weak Redox
F	25-35	10YR3/6	--	10YR5/2	fscl	30	Strong Redox
F	35-45	10YR3/6	--	10YR5/2	fscl	30	Strong Redox
F	45-55	10YR5/2	7.5YR5/8	10YR5/2	fscl	29	Strong Redox
F	55-65	10YR3/6	7.5YR5/8	10YR5/2	fsl	15	Strong Redox
F	65-75	10YR3/6	7.5YR5/8	10YR5/2	fsl	15	Strong Redox
F	75-85	7.5YR5/8	7.5YR5/8	10YR5/2	fsl	15	Strong Redox
F	85-95	N/A	N/A	N/A	N/A	N/A	N/A

Upper Marlboro

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
G	0-5	10YR3/3	--	--	fsl	15	--
G	5-15	10YR3/3	--	--	fsl	15	--
G	15-25	10YR4/6	--	10YR5/2	fsl	25	Weak Redox
G	25-35	10YR4/6	7.5YR5/8	10YR5/2	fsl	25	Weak Redox
G	35-45	10YR4/6	7.5YR5/8	10YR5/2	fsl	25	Weak Redox
G	45-55	10YR4/6	7.5YR5/8	5GY5/1	fsl	25	Weak Redox
G	55-65	10YR4/6	7.5YR5/8	5GY5/1	fsl	25	Strong Redox
G	65-75	10YR4/6	7.5YR5/8	5GY5/1	fsl	25	Strong Redox
G	75-85	7.5YR5/8	--	10YR5/2	fsl	16	Strong Redox
G	85-95	7.5YR5/8	--	10YR5/2	fsl	15	Strong Redox

Upper Marlboro

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
H	0-5	10YR3/3	--	--	fsl	15	--
H	5-15	10YR3/3	--	--	fsl	15	--
H	15-25	10YR5/4	--	--	fsl	25	--
H	25-35	10YR5/4	--	10YR5/2	fscl	30	Weak Redox
H	35-45	10YR4/4	7.5YR5/8	10YR5/2	fscl	30	Strong Redox
H	45-55	10YR4/4	7.5YR5/8	10YR5/2	fscl	35	Strong Redox
H	55-65	10YR4/4	7.5YR5/8	10YR5/2	fscl	35	Strong Redox
H	65-75	5GY5/1	7.5YR5/8	--	fscl	35	Strong Redox
H	75-85	5GY5/1	7.5YR5/8	--	fscl	35	Strong Redox
H	85-95	5GY5/1	7.5YR5/8	--	fsl	20	Strong Redox

Upper Marlboro

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
I	0-5	5YR4/4	--	--	fsl	15	--
I	5-15	10YR5/4	--	10YR5/2	fsl	15	Weak Redox
I	15-25	10YR5/4	--	10YR5/2	fsl	20	Weak Redox
I	25-35	10YR5/4	7.5YR5/8	5GY5/1	fsl	22	Strong Redox
I	35-45	10YR5/4	7.5YR5/8	5GY5/1	fscl	28	Strong Redox
I	45-55	5GY5/1	7.5YR5/8	--	fscl	28	Strong Redox
I	55-65	5GY5/1	7.5YR5/8	--	fscl	28	Strong Redox
I	65-75	5GY5/1	7.5YR5/8	--	fscl	28	Strong Redox
I	75-85	5GY5/1	7.5YR5/8	--	fscl	28	Strong Redox
I	85-95	5GY5/1	7.5YR5/8	--	fsl	15	Strong Redox

Upper Marlboro

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
J	0-5	10YR4/4	--	--	fsl	15	--
J	5-15	10YR5/4	--	10YR5/2	fsl	15	--
J	15-25	10YR5/4	--	10YR5/2	fsl	27	Weak Redox
J	25-35	10YR5/4	7.5YR5/8	10YR5/2	fscl	30	Weak Redox
J	35-45	10YR5/4	7.5YR5/8	10YR5/2	fscl	30	Weak Redox
J	45-55	10YR5/4	7.5YR5/8	10YR5/2	fsl	27	Weak Redox
J	55-65	10YR5/4	7.5YR5/8	10YR5/2	fsl	27	Weak Redox
J	65-75	10YR5/4	7.5YR5/8	10YR5/2	fsl	15	Weak Redox
J	75-85	10YR5/4	7.5YR5/8	5GY5/1	fsl	15	Strong Redox
J	85-95	5GY5/1	7.5YR5/8	N7	fsl	15	Strong Redox

Holtwood

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
A	0-10	10YR3/6	--	--	sil	12	--
A	10-20	10YR3/6	--	--	sil	12	--
A	20-30	10YR3/6	--	--	sil	12	--
A	30-40	10YR3/6	--	--	sil	15	--
A	40-50	7.5YR5/8	--	--	sil	22	--
A	50-60	7.5YR5/8	--	--	sicl	30	--
A	60-70	7.5YR5/8	--	--	sicl	30	--
A	70-80	7.5YR5/8	--	--	sicl	30	Common Rocks
A	80-90	5YR5/8	--	--	sicl	30	--

Holtwood

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
B	0-10	10YR3/6	--	--	sil	10	--
B	10-20	10YR3/6	--	--	sil	10	--
B	20-30	10YR3/6	--	--	sil	15	--
B	30-40	7.5YR5/8	--	--	sil	20	--
B	40-50	7.5YR5/8	--	--	sil	20	--
B	50-60	7.5YR5/8	--	--	sil	20	--
B	60-70	7.5YR5/8	--	--	sil	20	--
B	70-80	7.5YR5/8	--	--	sicl	30	--
B	80-90	7.5YR5/8	--	--	sicl	30	--

Holtwood

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
C	0-10	10YR3/4	--	--	sil	10	--
C	10-20	10YR3/4	--	--	sil	10	--
C	20-30	10YR4/4	--	--	sil	15	--
C	30-40	7.5YR5/8	--	--	sil	20	Common Rocks
C	40-50	7.5YR5/8	--	--	sil	25	--
C	50-60	7.5YR5/8	--	--	sil	25	--
C	60-70	5YR5/8	N/A	N/A	sicl	30	Weak Redox
C	70-80	5YR5/8	N/A	N/A	sicl	30	Weak Redox
C	80-90	5YR5/8	N/A	N/A	sicl	30	Weak Redox

Holtwood

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
D	0-10	10YR3/4	--	--	sil	10	--
D	10-20	10YR3/4	--	--	sil	10	--
D	20-30	10YR5/6	--	--	sil	12	--
D	30-40	7.5YR5/8	--	--	sil	20	--
D	40-50	7.5YR5/8	--	--	sicl	28	Common Rocks
D	50-60	7.5YR5/8	N/A	N/A	sicl	30	Common Rocks, Weak Redox
D	60-70	7.5YR5/8	N/A	N/A	sicl	30	Weak Redox
D	70-80	5YR5/8	N/A	N/A	sicl	30	Weak Redox
D	80-90	5YR5/8	N/A	N/A	sicl	30	Weak Redox

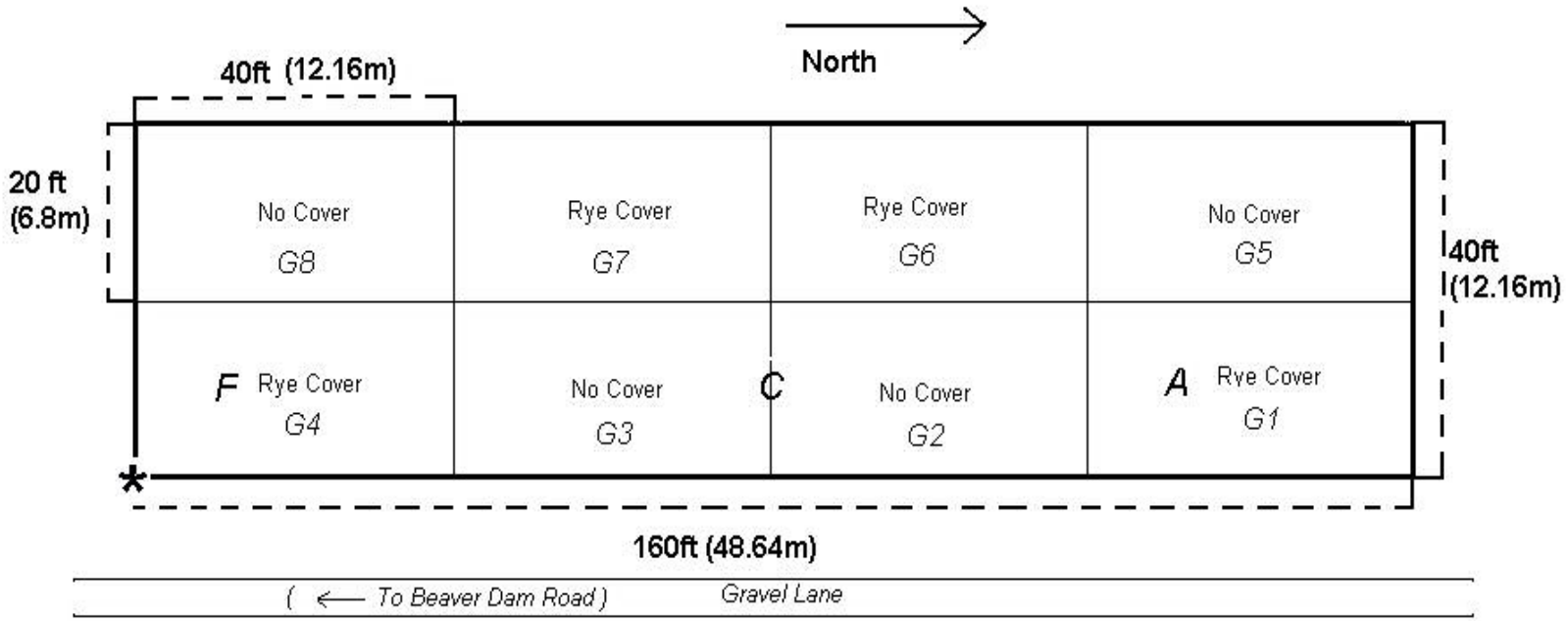
Holtwood

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
E	0-10	10YR3/6	--	--	sil	10	Few Rocks
E	10-20	10YR3/6	--	--	sil	10	--
E	20-30	10YR4/6	--	--	sil	12	--
E	30-40	7.5YR5/8	--	--	sil	20	--
E	40-50	7.5YR5/8	--	--	sicl	28	--
E	50-60	7.5YR5/8	--	--	sicl	30	--
E	60-70	5YR5/8	--	--	sicl	30	--
E	70-80	5YR5/8	N/A	N/A	sicl	30	Weak Redox
E	80-90	5YR5/8	N/A	N/A	sicl	30	Weak Redox

Holtwood

Description Location	Depth (cm)	Matrix Munsell Color	Oxidized Zone Munsell Color	Reduced Zone Munsell Color	Texture Class (by Feel)	Estimated Clay (%)	Notes
F	0-10	10YR3/4	--	--	sil	10	--
F	10-20	10YR3/4	--	--	sil	10	--
F	20-30	10YR5/6	--	--	sil	12	--
F	30-40	7.5YR5/8	--	--	sil	20	--
F	40-50	7.5YR5/8	--	--	sicl	28	--
F	50-60	7.5YR5/8	--	--	sicl	30	--
F	60-70	7.5YR5/8	N/A	N/A	sicl	30	Weak Redox
F	70-80	5YR5/8	N/A	N/A	sicl	30	Weak Redox, Common Rocks
F	80-90	5YR5/8	N/A	N/A	sicl	30	Weak Redox

Figure B.1 Hayen farm (Beltsville WREC) Plot diagram for active C study in Field F-25F
(Field only plowed [2000] and cropped once [2001].
Field was in long-term sod prior to that.)



*: This plot reference point is 51.8m from the fence at the edge of Beaver Dam Road and 13 m from the gravel lane

Letters in italics indicate location of profile description

Figure B.2

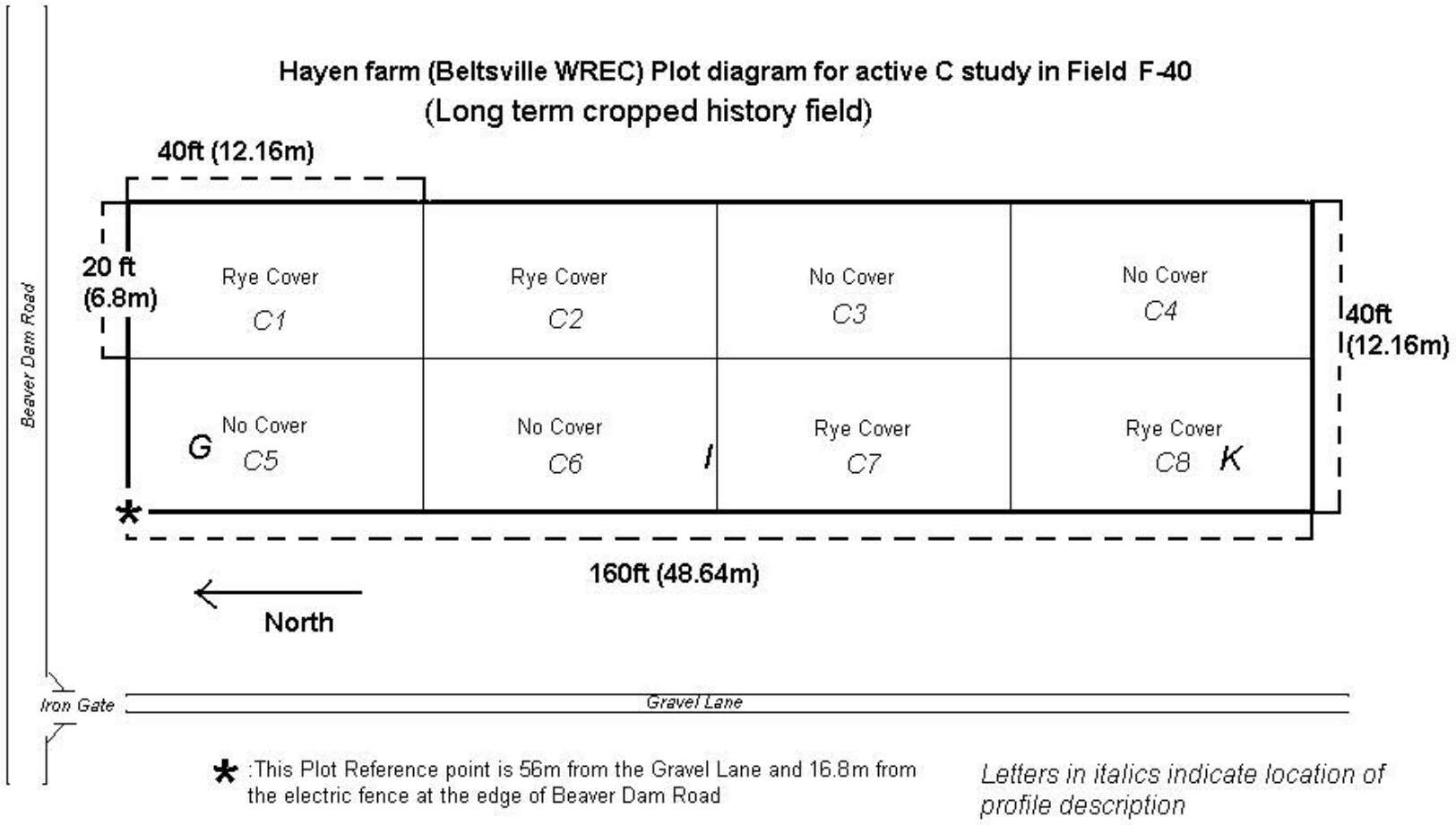

Hayen farm (Beltsville WREC) Plot diagram for active C study in Field F-40
(Long term cropped history field)
40ft (12.16m)
20 ft
(6.8m)
Rye Cover
C1
Rye Cover
C2
No Cover
C3
No Cover
C4
40ft
(12.16m)
G
No Cover
C5
No Cover
C6
I
Rye Cover
C7
Rye Cover
C8
K
160ft (48.64m)
North
Beaver Dam Road
Iron Gate
Gravel Lane
* :This Plot Reference point is 56m from the Gravel Lane and 16.8m from the electric fence at the edge of Beaver Dam Road
Letters in italics indicate location of profile description

Figure B.3

Field and subplot layout at Keedysville, Maryland

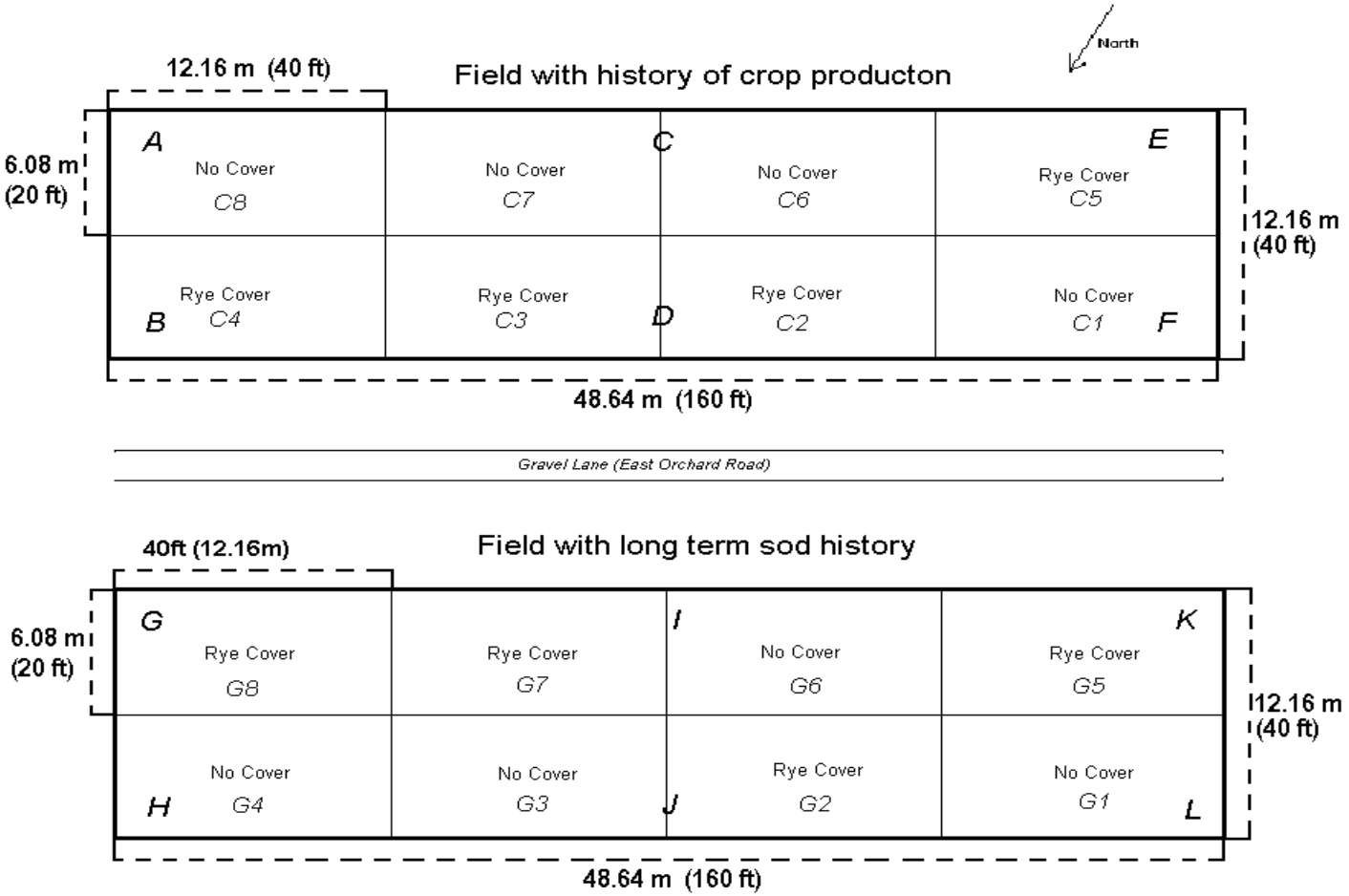


Figure B.4 **Upper Marlboro WREC active C study field plot layouts for Field 105 and an adjacent long term sod area to be brought into production**

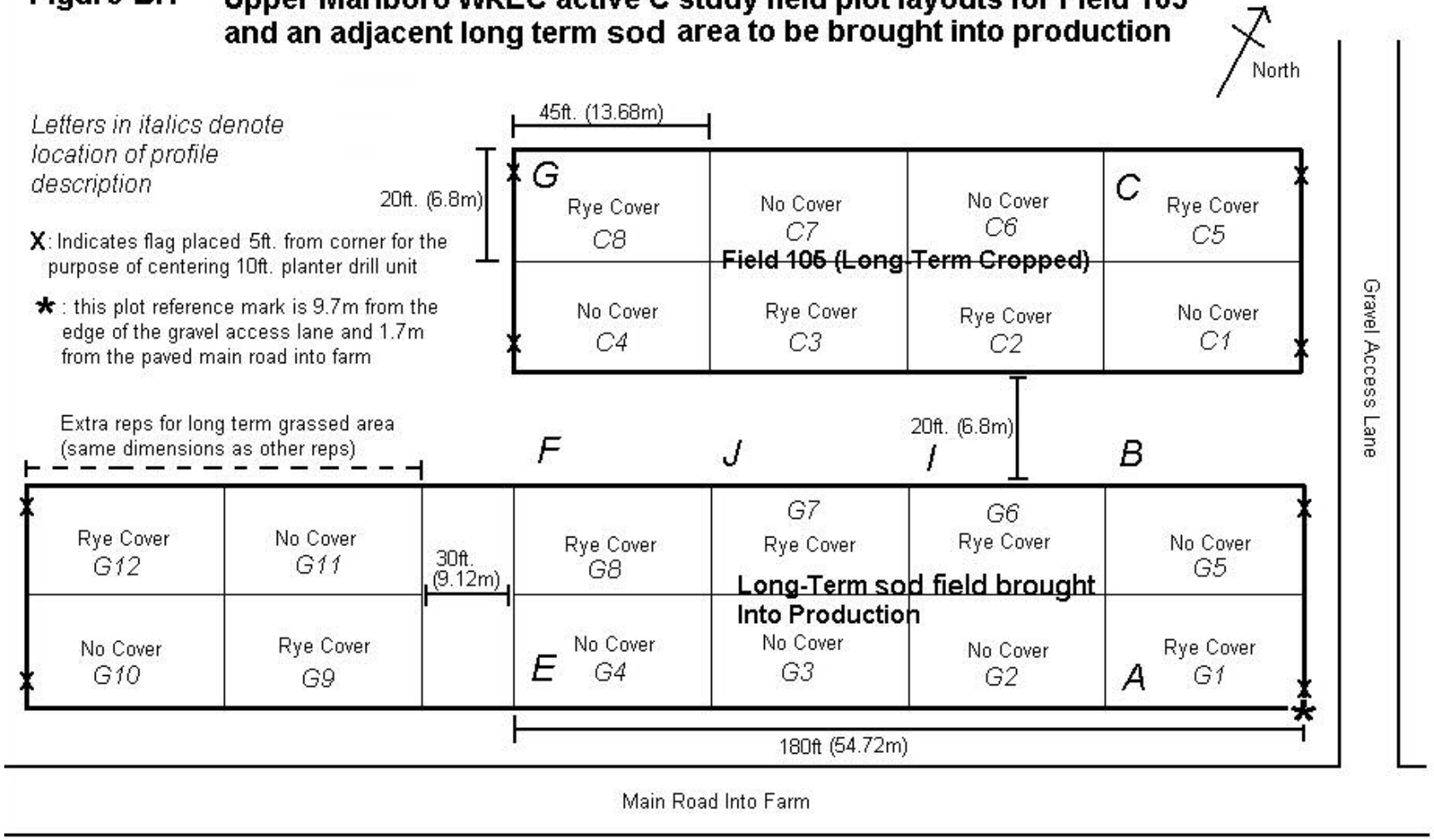
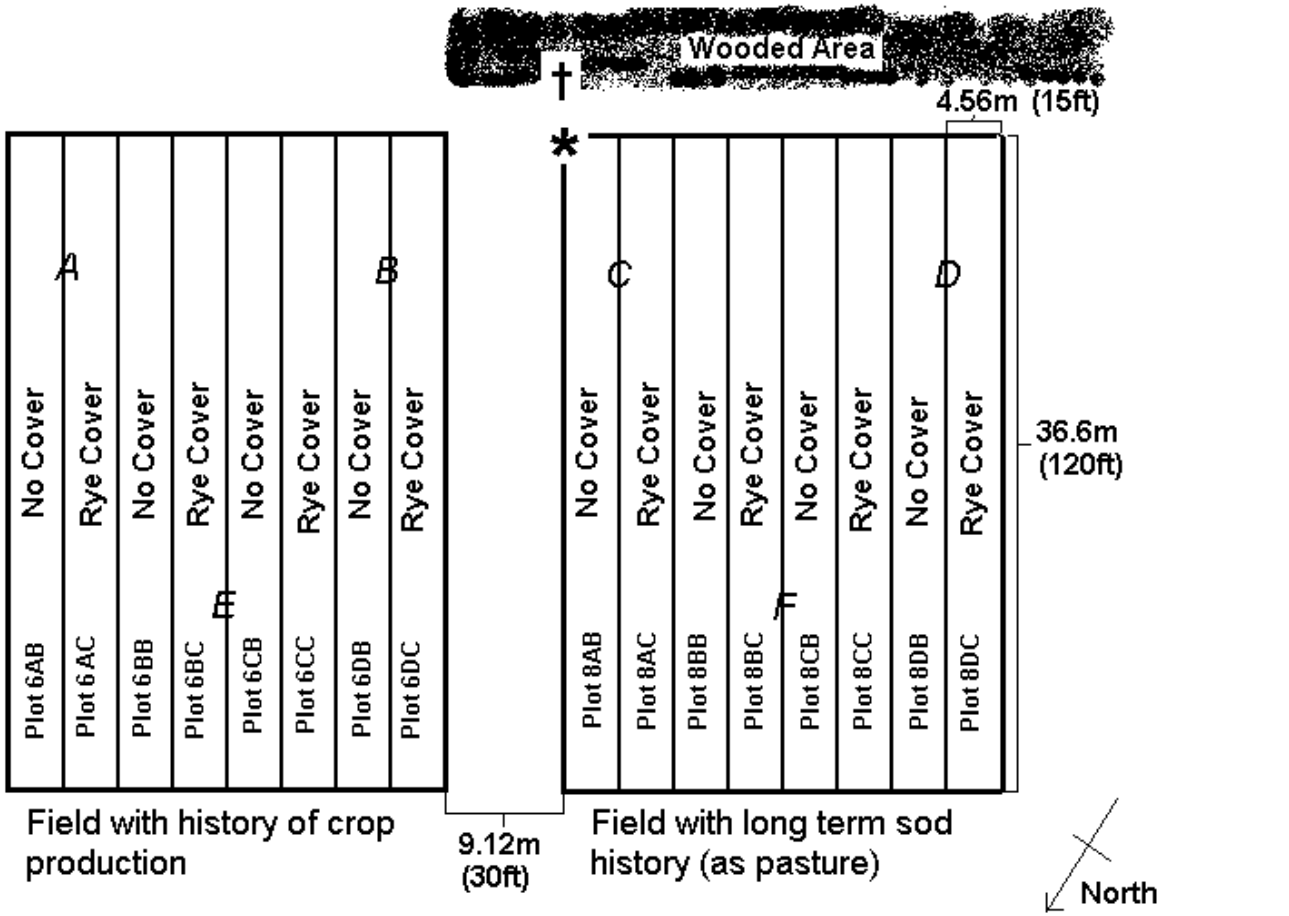


Figure B.5 Field and subplot layout at Holtwood, Pennsylvania



*: This plot reference point is exactly 40ft into the field from the green iron post (†) at the edge of the woods.

Appendix C: Analysis of systematic plot layout at Holtwood for non-random variability among variables tested

INTRODUCTION

The portion of this research conducted at Holtwood, PA was on a commercial farm (Cedar Meadow Farm, 679 Hilldale Road, Holtwood, PA 17532; Steve Groff, Proprietor and Manager). To simplify operations for the manager of this site, subplots were long adjacent strips that alternated systematically (See Appendix B, Figure B.5), between rye and no-rye treatments.

METHODS

Analysis was conducted in SYSTAT version 10 (SYSTAT Software Inc., Point Richmond, CA). All dependent variables analyzed in Chapters one and two were examined graphically against each subplot. As seen in Appendix B, Figure B.5 the subplots follow the spatial gradient. Subplot labels indicate field number as designated by the farm manager, block, and cover crop treatment. For example 6AB denotes Field 6, Block A, no cover (B = Bare, C = Rye Cover). Field 6 had long term cropping history while field 8 was the long term sod history field.

RESULTS

Figures C.1 – C12 (p. 179 – 184) show graphical results of plots of dependent variables vs. the spatial gradient. Expected differences due to management history can be seen in variables in Figures C.1 – C.7. These do not constitute unwanted systematic trends. Soybean yields, soybean biomass, and mineralizable N may show slight

systematic behavior as one examines the data moving from left to right in Figures C.6, C.7, and C.11, respectively. This behavior, if indeed it is a systematic trend, should be statistically accounted for, however through the blocking scheme in these fields. No other variables exhibit notable systematic trends.

APPENDIX C FIGURES

Figure C.1. Initial Labile C vs. Subplots (Spatial Gradient) at Holtwood.

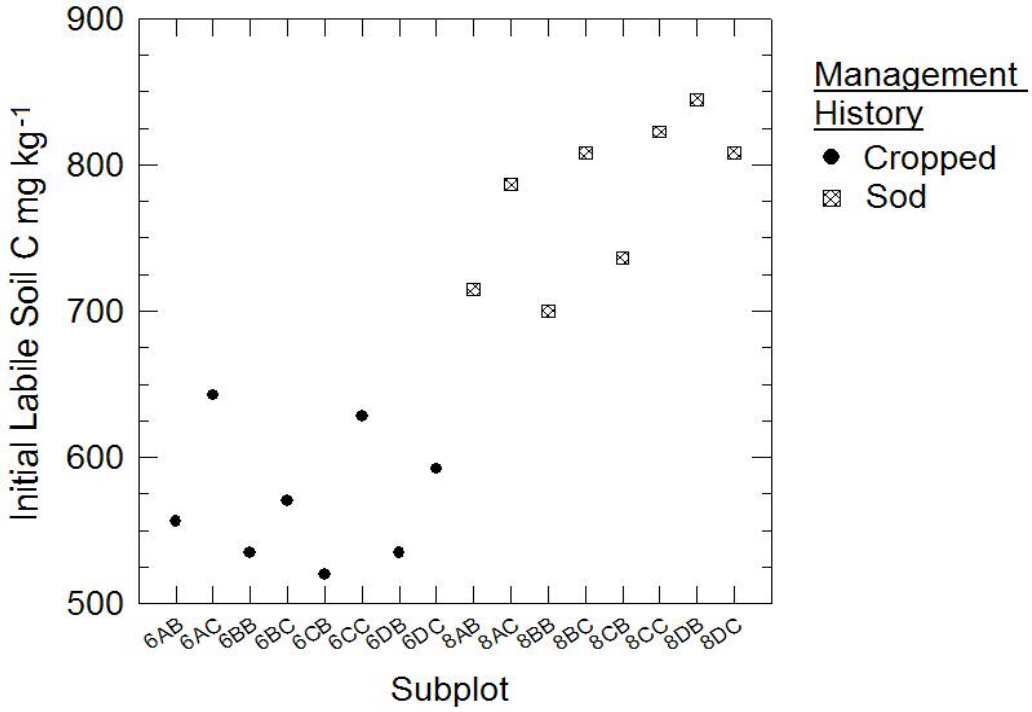


Figure C.2. Aug. 2002 Labile C vs. Subplots (Spatial Gradient) at Holtwood.

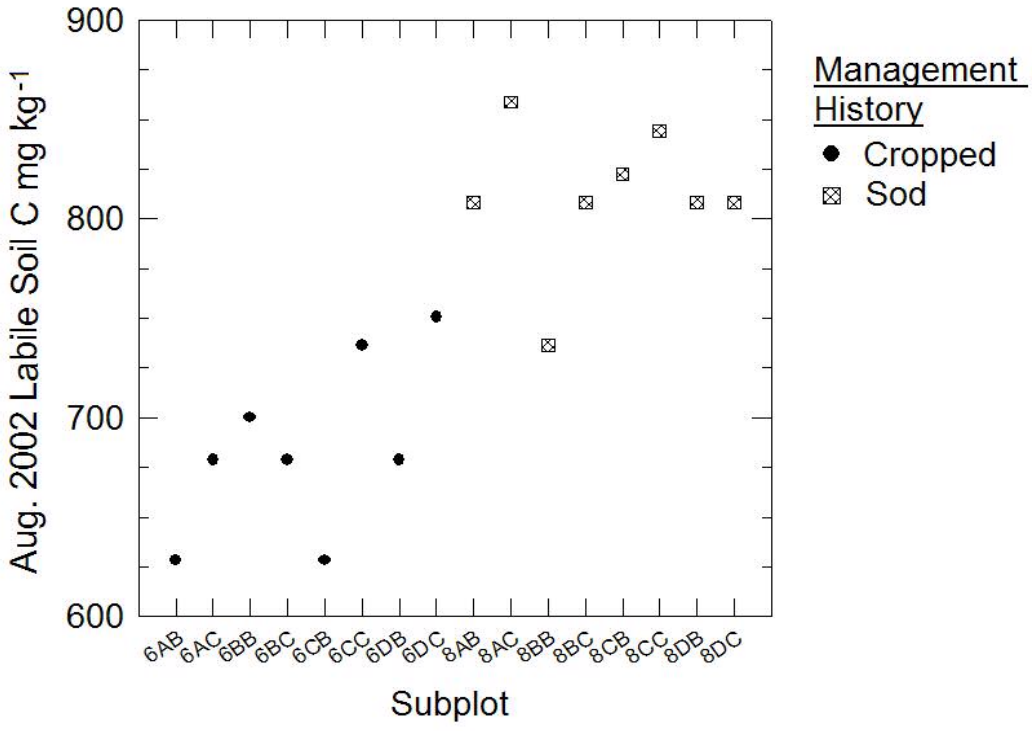


Figure C.3. Aug. 2003 Labile C vs. Subplots (Spatial Gradient) at Holtwood.

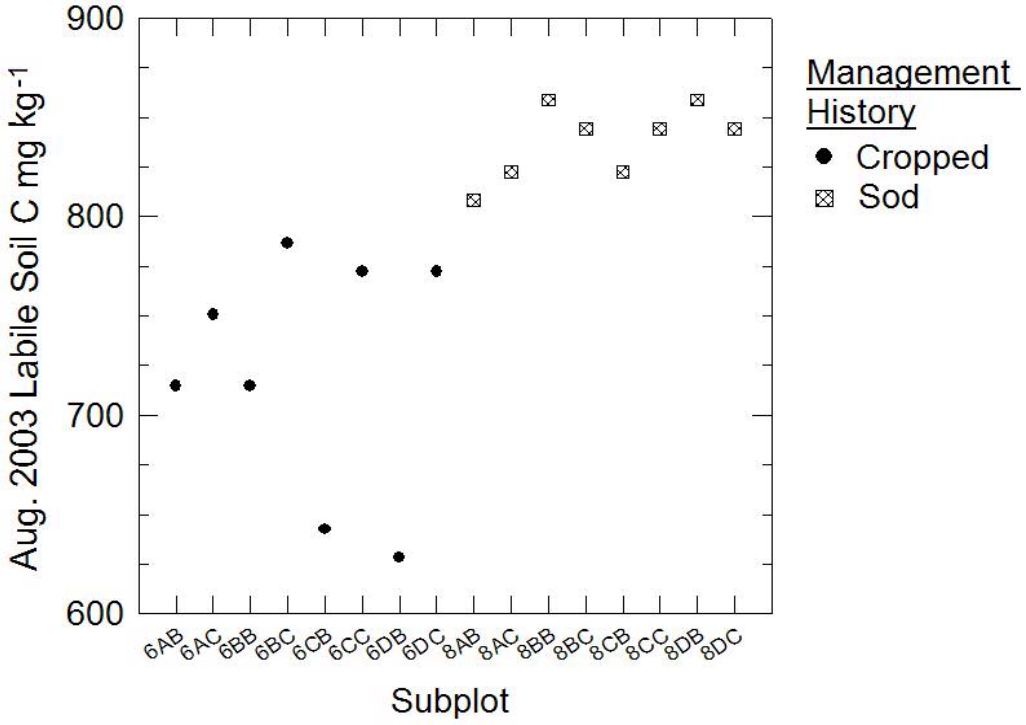


Figure C.4. Initial Total C vs. Subplots (Spatial Gradient) at Holtwood.

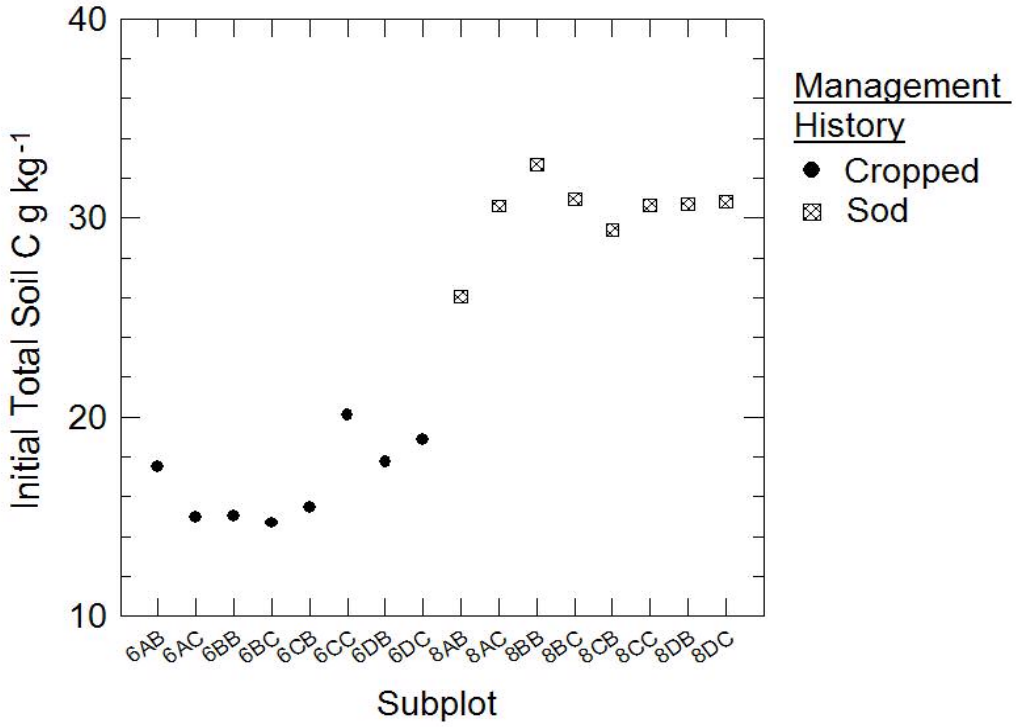


Figure C.5. Nov. 2003 Total Soil C vs. Subplots (Spatial Gradient) at Holtwood.

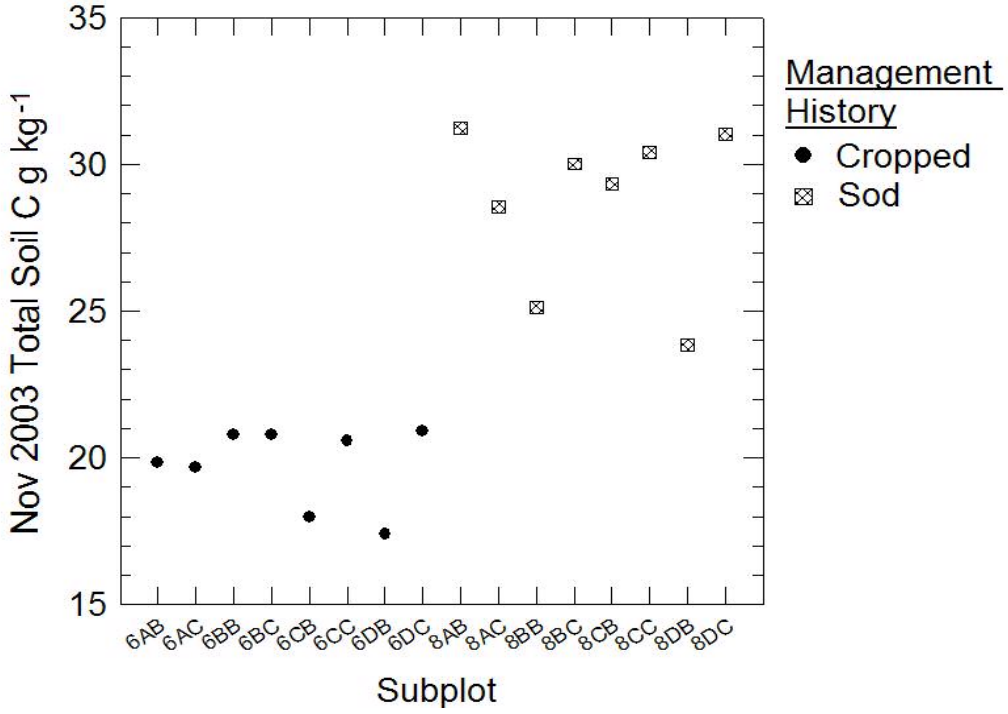


Figure C.6. Soybean Yield in 2002 vs. Subplots (Spatial Gradient) at Holtwood.

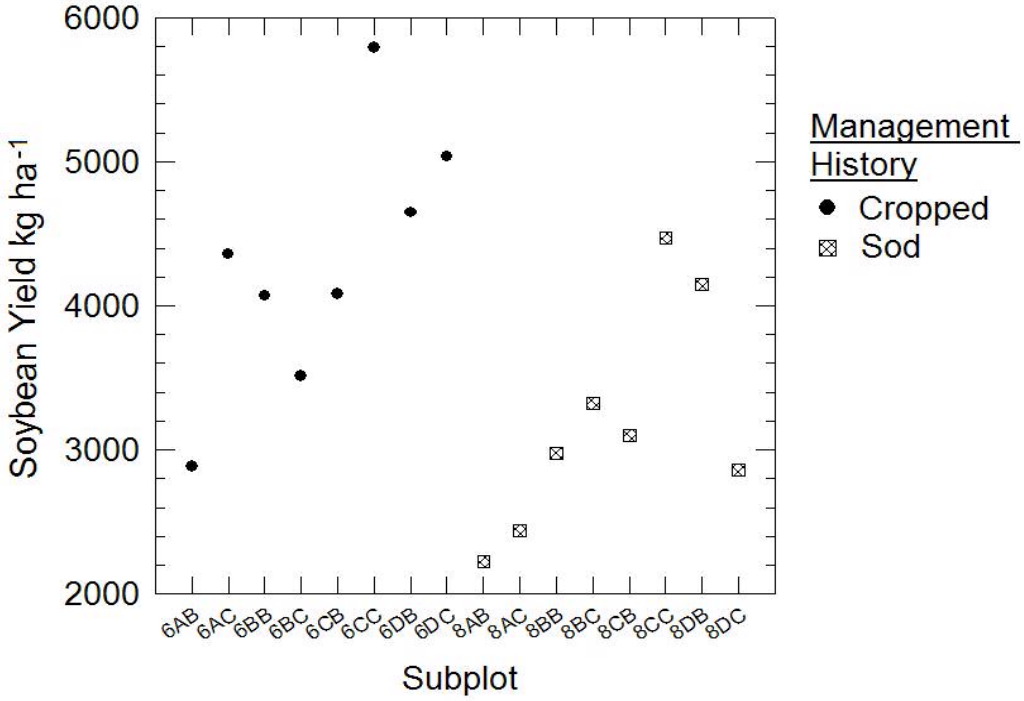


Figure C.7. Soybean Biomass in 2002 vs. Subplots (Spatial Gradient) at Holtwood.

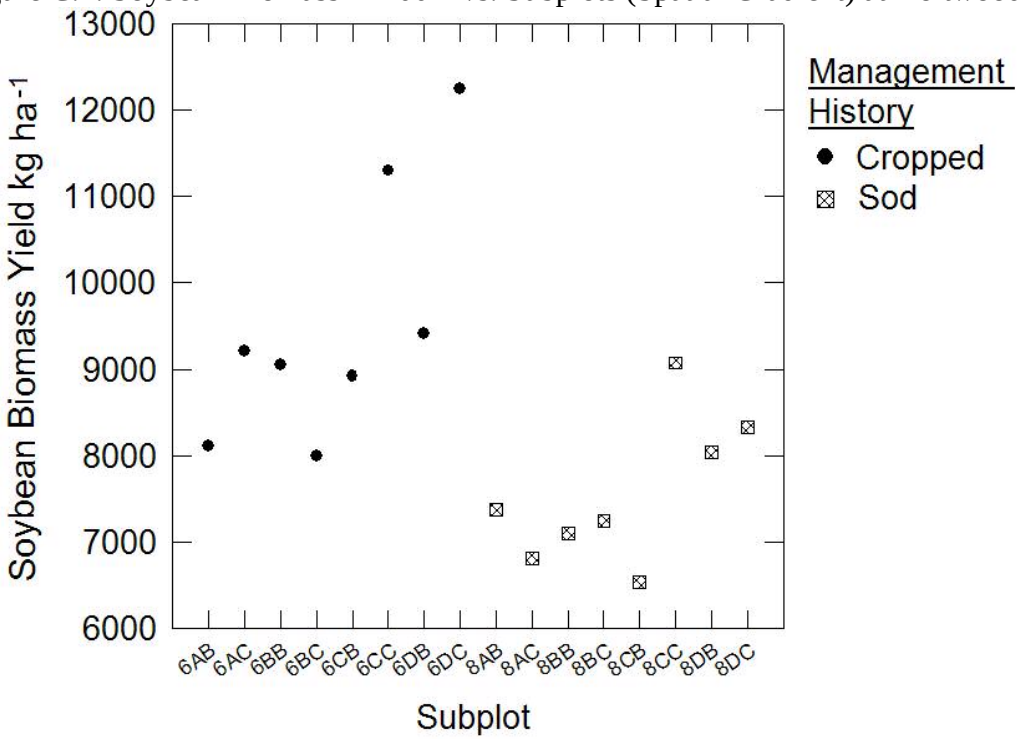


Figure C.8. Corn Grain Yield in 2003 vs. Subplots (Spatial Gradient) at Holtwood.

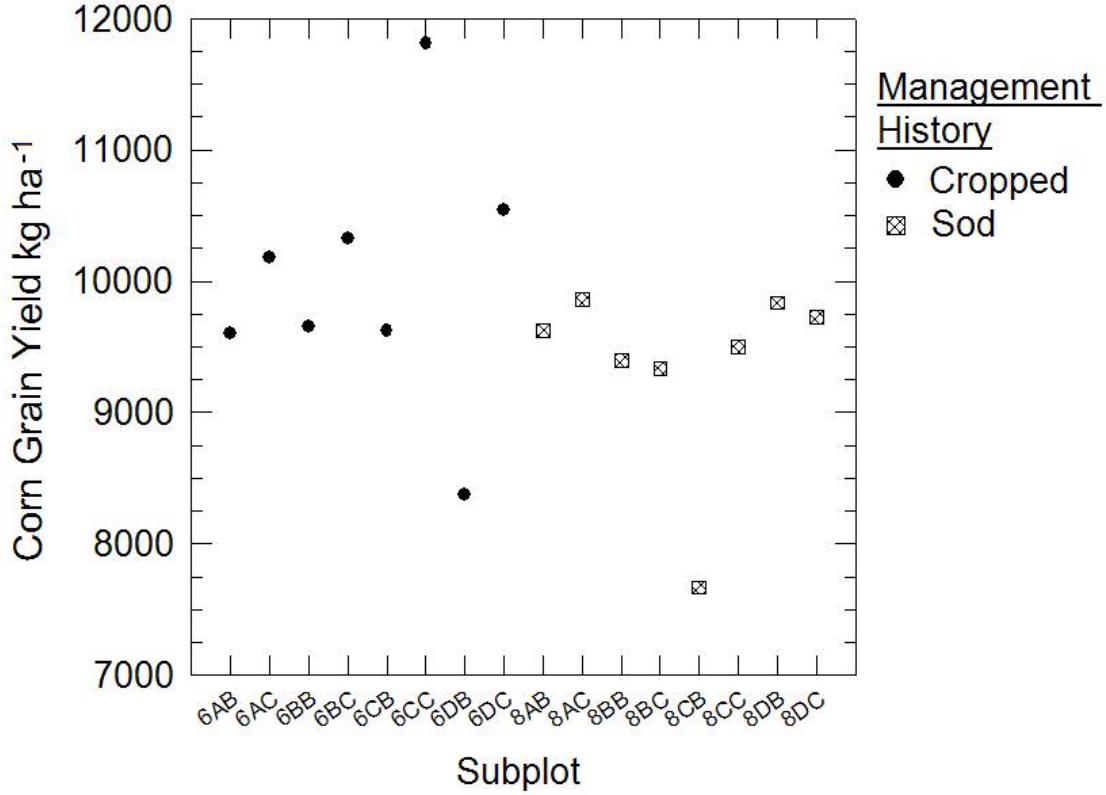


Figure C.9. Corn Biomass in 2003 vs. Subplots (Spatial Gradient) at Holtwood.

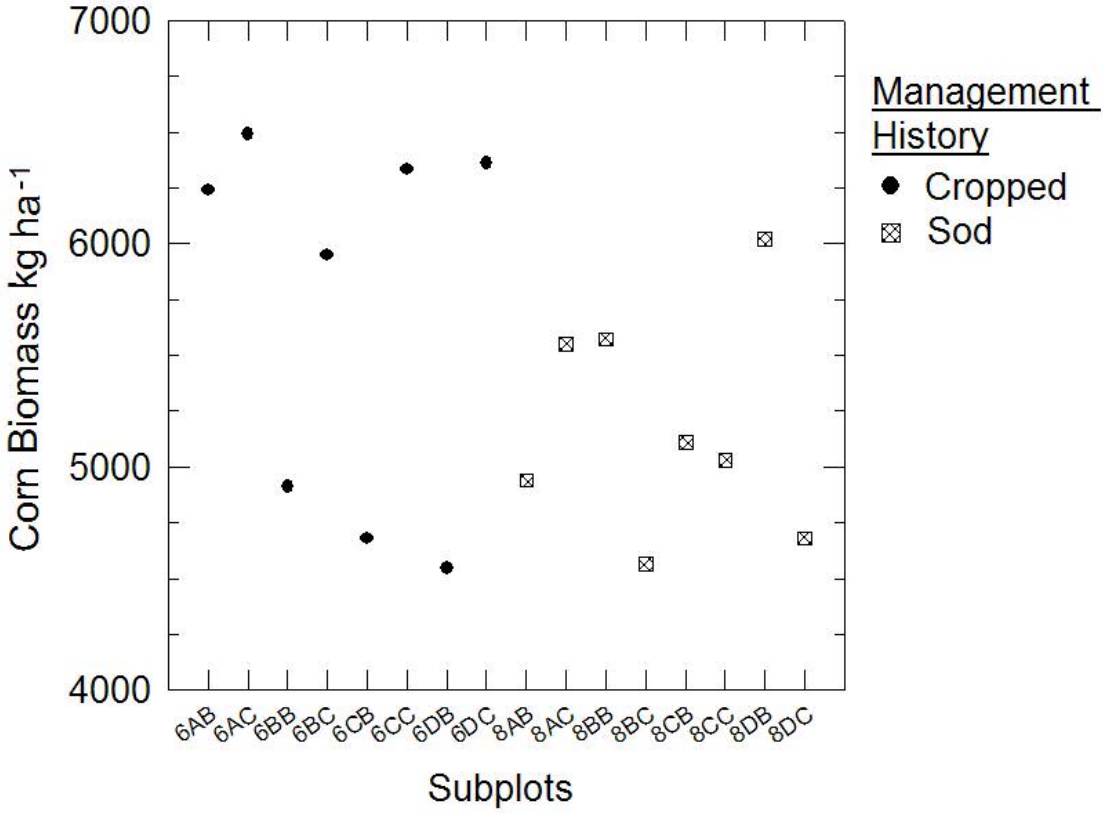


Figure C.10. Corn Biomass in 2003 vs. Subplots (Spatial Gradient) at Holtwood.

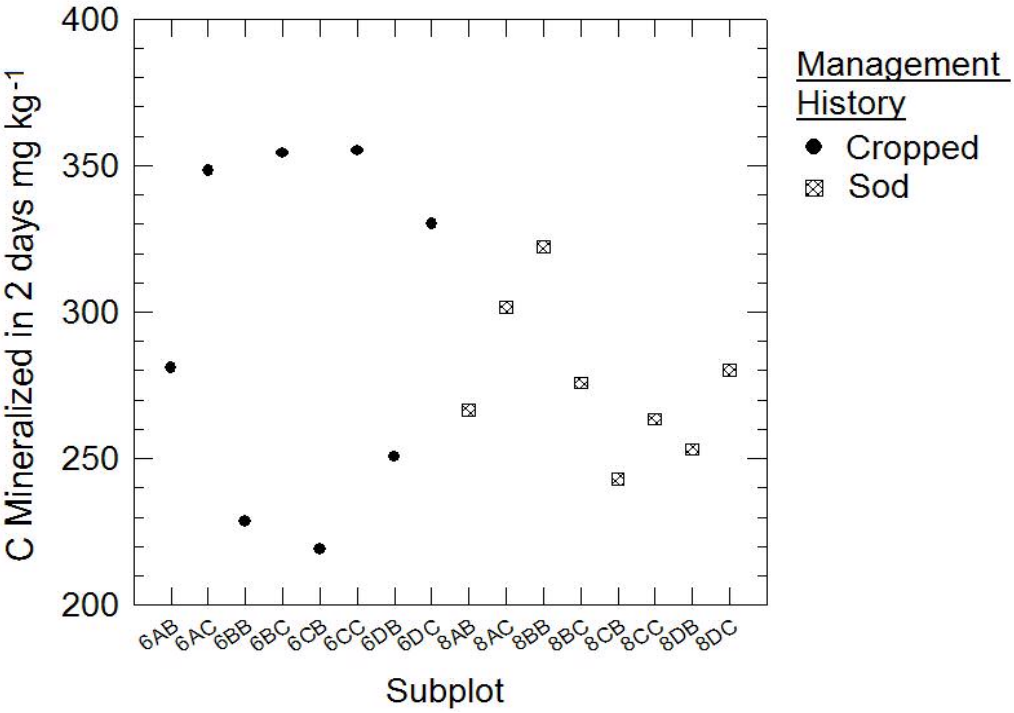


Figure C.11. Mineralizable N (16 Day Incubation) vs. Subplots (Spatial Gradient) at Holtwood.

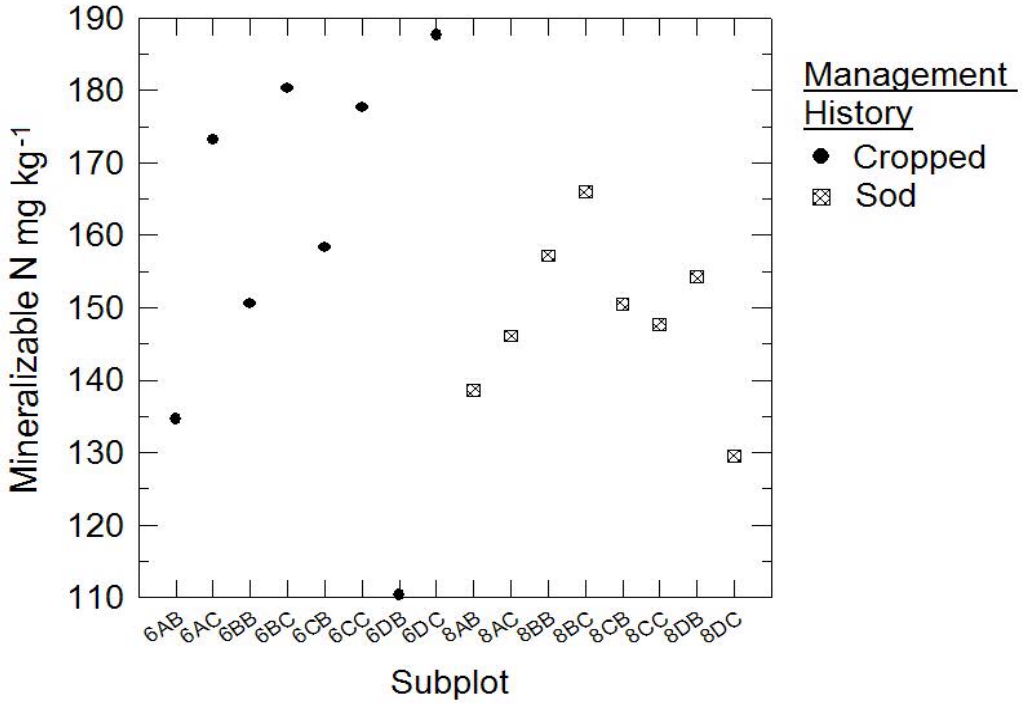
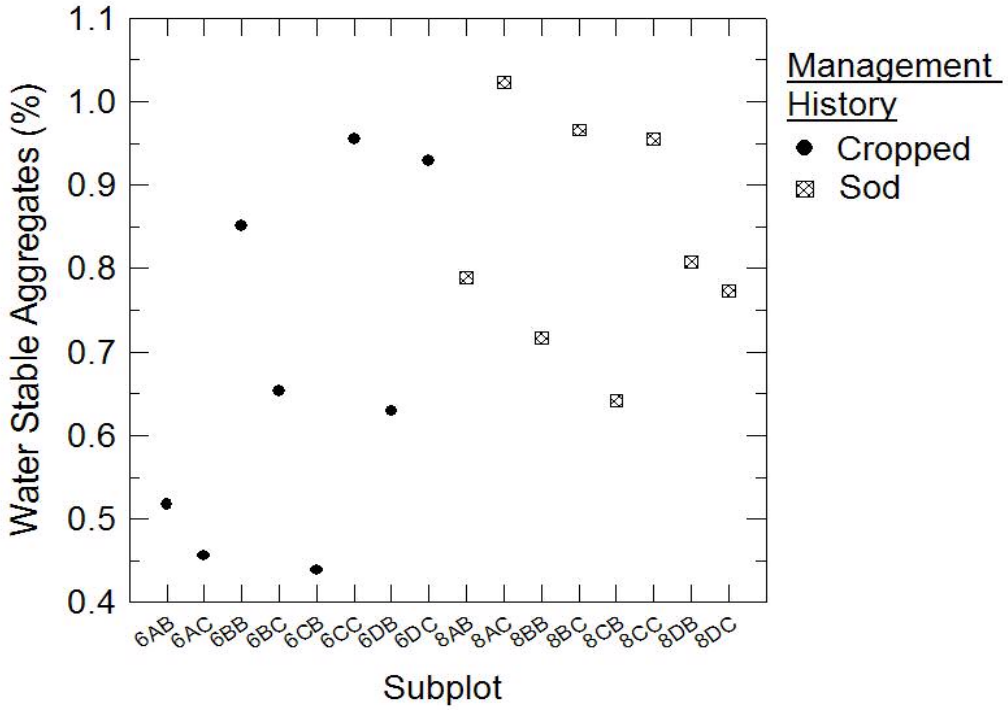


Figure C.12. Percentage of Water Stable Soil Aggregates vs. Subplots (Spatial Gradient) at Holtwood.



Appendix D: Sample SYSTAT commands.

A: ANOVA of dependent variables (in this case initial labile soil C) within one site (Beltsville):

Step 1:

```
USE "C:\Documents and Settings\Shawn T. Lucas\My Documents\MS Thesis 2004\Active C
Thesis\stats\AllData1Rev.SYD"

SELECT (SITE$= "Belts")

GLM
CATEGORY HISTORY$ TREAT$ BLOCK / EFFECT
MODEL AC2INIT = CONSTANT +
HISTORY$+TREAT$+TREAT$*HISTORY$+BLOCK(HISTORY$)+TREAT$*BLOCK(HISTORY$)
ESTIMATE
```

Step 2:

```
HYPOTHESIS
EFFECT=HISTORY$
ERROR=BLOCK(HISTORY$)
STANDARDIZE=WITHIN
TEST
```

Step 3:

```
HYPOTHESIS
EFFECT=TREAT$*HISTORY$
ERROR=TREAT$*BLOCK(HISTORY$)
STANDARDIZE=WITHIN
TEST
```

Where TREAT$ is cover crop treatment (COVER) and HISTORY$ is field management history (MH). Step 1 is the basic model. Step 2 tests the whole-plot effect of history using the correct split-plot error term. Step 3 tests the whole-plot by subplot interaction COVER*MH using the correct split-plot error term.

B: ANOVA of dependent variables (in this case initial labile soil C) across all sites:

Step 1:

```
GLM
CATEGORY SITE$ HISTORY$ BLOCK TREAT$ / EFFECT
MODEL AC2INIT = CONSTANT +
SITE$+HISTORY$(SITE$)+BLOCK(HISTORY$(SITE$))+TREAT$+TREAT$*BLOCK(HISTORY$(SITE$))+TRE
AT$*HISTORY$(SITE$)
```

```
ESTIMATE
```

Step 2:

```
HYPOTHESIS
EFFECT=HISTORY$(SITE$)
ERROR=BLOCK(HISTORY$(SITE$))
STANDARDIZE=WITHIN
TEST
```

Step 3:

```
HYPOTHESIS
EFFECT=TREAT$*HISTORY$(SITE$)
ERROR=TREAT$*BLOCK(HISTORY$(SITE$))
STANDARDIZE=WITHIN
TEST
```

where SITE$ is the site effect (SITE) which constitutes the true replication in the model. Step 1 is the basic model. Step 2 tests the whole-plot effect of MH(SITE). Means are not generated for this term because of the nested nature of the term. The significance of the term is tested. Step 3 tests the whole-plot by subplot interaction COVER*(MH(SITE)). Step 2 and step 3 both use the correct split-plot error terms.

C: ANOVA of standardized yield variables at one site:

These analyses followed the same method used in part A of this appendix.

D: ANOVA of standardized yield variables (in this case crop grain in 2002) across all sites:

Step 1:

```
GLM
CATEGORY HISTORY$ TREAT$ BLOCK SITE$ / EFFECT
MODEL STDYLD02 = CONSTANT +
HISTORY$+TREAT$+TREAT$*HISTORY$+BLOCK(HISTORY$(SITE$))+TREAT$*BLOCK(HISTORY$(SITE$
))
ESTIMATE
```

Step 2:

```
HYPOTHESIS
EFFECT=HISTORY$
ERROR=BLOCK(HISTORY$(SITE$))
STANDARDIZE=WITHIN
TEST
```

Step 3:

```
HYPOTHESIS
EFFECT=TREAT$*HISTORY$
ERROR=TREAT$*BLOCK(HISTORY$(SITE$))
STANDARDIZE=WITHIN
TEST
```

Step 1 is the basic model, Step 2 tests whole-plot effects, and Step 3 tests interaction effects as previously described.

E: ANOVA of response variables (in this case crop grain response in 2002) within one site:

```
USE "C:\Documents and Settings\Shawn T. Lucas\My Documents\MS Thesis 2004\Active C Thesis\stats\allresp1.syd"

SELECT (SITE$= "Belts")

GLM
CATEGORY HISTORY$ / EFFECT
MODEL RESGR02 = CONSTANT + HISTORY$
ESTIMATE
```

The above commands test the main effect of MH on grain response at Beltsville.

F: ANOVA of response variables (in this case crop grain response in 2002) across all sites:

```
GLM
CATEGORY HISTORY$ SITE$ / EFFECT
MODEL RESGR02 = CONSTANT + HISTORY$(SITE$)+SITE$
ESTIMATE
```

The above commands test the main nested effect of (MH(SITE)) on grain response across all sites. Due to the nested nature of the variable means are not generated of (MH(SITE)) but the significance of the overall effect is tested.

G: Typical correlation (in this case crop grain response in 2003 vs initial labile soil C and initital total soil C):

```
USE "C:\Documents and Settings\Shawn T. Lucas\My Documents\MS Thesis 2004\Active C Thesis\stats\allresp1.syd"
```

```
CORR

PEARSON RESGR03*ME3AC2INIT INTC_GKG / PROB
```

The above commands were used to examine relationships between variables.

F: Typical production of a plot showing a relationship between variables (in this case crop grain response in 2002 vs initial labile soil C) across all sites:

```
PLOT RESGR03*ME3AC2INIT / ELL
```

The above commands were used to graphically examine and present relationships between variables.

G: Typical SYSTAT 10 commands for ANOVA used to test the effects of rye on various dependent variables (in this case total biomass) at individual experiments in Chapter 4:

```
BY SITE$ FIELD$

GLM
CATEGORY TREAT$ BLOCK / EFFECT
MODEL BIOMASS = CONSTANT + TREAT$+BLOCK

ESTIMATE
```

H: Typical SYSTAT 10 commands for ANOVA used to test the effects of rye on various dependent variables (in this case total biomass) across experiments in Chapter 4:

```
GLM
MODEL BIOMASS = CONSTANT + FIELD$+TREAT$+BLOCK(FIELD$)

ESTIMATE
```

REFERENCE LIST

Chapter One

Allison, F.E. 1973. Soil organic matter and its role in crop production. Dev. Soil Sci. 3. Elsevier, Amsterdam.

Alvarez, R., M.E. Russo, P. Prystupa, J.D. Schneider, and L. Blotta. 1998a. Soil carbon pools under conventional and no-tillage systems in the Argentine Rolling Pampa. Agron. J. 90:138-143.

Alvarez, C.R., R. Alvarez, M.S. Grigera, and R.S. Lavado. 1998b. Associations between organic matter fractions and the active soil microbial biomass. Soil Biol. and Biochem. 30:767-773.

Alvarez, R., C.R. Alvarez, and H.S. Steinbach. 2002. Association between soil organic matter and wheat yield in humid Pampa of Argentina. Comm. Soil Sci. Plant Anal. 33:749-757.

Acton, D.F., and G.A. Padbury. 1993. A conceptual framework for soil quality assessment and monitoring. *In* D.F. Acton (Ed.) A Program to Assess and Monitor Soil Quality in Canada: Soil Quality Evaluation Program Summary. Research Branch, Agriculture and Agri-Food Canada: Ottawa, Ontario.

Angers, D.A., and G.R. Mehuys 1989. Effects of cropping on carbohydrate content and water stable aggregation of a clay soil. Can. J. Soil Sci. 69:373-380.

Arshad, M.A., and G.M. Coen. 1992. Characterization of soil quality: Physical and chemical criteria. Am. J. Altern. Agric. 7:25-31.

Banerjee, M.R., and S.J. Chapman. 1996. The significance of microbial biomass sulphur in soil. Biol. Fertil. Soils 22:116-125.

Bauer, A., and A.L. Black. 1981. Soil carbon, nitrogen, and bulk density comparisons in two cropland tillage systems after 25 years and in virgin grassland. Soil Sci. Soc. Am. J. 45:1166-1170.

Bauer, A., and A.L. Black. 1994. Quantification of the effect of soil organic matter content on soil productivity. Soil Sci. Soc. Am. J. 58:185-193.

Bauer, P.J., and W.J. Busscher, 1996. Winter cover and tillage influences on Coastal Plain cotton production. J. Product. Agric. 9:50-54.

Bell, M.J., P.W. Moody, R.D. Connolly, and B.J. Bridge. 1998. The role of active fractions of soil organic matter in physical and chemical fertility of Ferrosols. Aust. J. Soil Res. 36:809-819.

Bell, M.J., P.W. Moody, S.A. Yo, and R.D. Connoly. 1999. Using active fractions of soil organic matter as indicators of the sustainability of Ferrosol farming systems. Aust. J. Soil Res. 37:279-287.

Beyer, L, K. Sieling, and K. Pingpank. 1999. The impact of a low humus level in arable soils on microbial properties, soil organic matter quality and crop yield. Biol. Fertil. Soils 28:156-161.

Bezdicek, D.F., R.I. Papendick, and R. Lal. 1996. Importance of soil quality to health and sustainable land management. p. 1-8. *In* J.W.Doran and A.J. Jones (ed.) Methods for assessing soil quality. SSSA Spec. Publ. 35. SSSA, Madison, WI.

Biederbeck, V.O., H.H. Janzen, C.A. Campbell, R.P. Zentner. 1994. Labile soil organic matter as influenced by cropping practices in an arid environment. Soil Biol. Biochem. 26:1647-1656

Blair, G.J., R.D.B. Lefroy, and L. Lisle. 1995. Soil carbon fractions based on their degree of oxidation and the development of a carbon management index for agricultural systems. Aust. J. Agric. Res. 46:1459-1466.

Blair, G.J., R. Lefroy, A. Whitbread, N. Blair, and A. Conteh. 2001. The development of the $KMnO_4$ to determine labile carbon in soil and its use in a carbon management index. p. 323-337. *In* R. Lal, J.M. Kimble, R.F. Follett, and B.A. Stewart (ed.) Assessment methods for soil carbon. Lewis Publishers, Boca Raton, FL.

Blair, N., and G.J. Crocker. 2000. Crop rotation effects on soil carbon and physical fertility of two Australian soils. Aust. J. Soil Res. 38:71-84.

Blevins, R.L., W.W. Frye, and M.S. Smith. 1985. The effects of conservation tillage on soil properties. p. 99-110. In F.M. D'Itri (ed.) A systems approach to conservation tillage. Lewis Publishers, Chelsea, MI.

Blevins, R.L., J.H. Herbeck, and W.W. Frye. 1990. Legume cover crops as a nitrogen source for no-till corn and grain sorghum. Agron. J. 82:769-772.

Bowman, R.A., M.F. Vigil, D.C. Nielsen, and R.L. Anderson. 1999. Soil organic matter changes in intensively cropped dryland systems. Soil Sci. Soc. Am. J. 63:186-191.

Bowman, R.A., and R.L. Anderson. 2002. Conservation Reserve Program: effects on soil organic carbon and preservation when converting back to cropland in northeastern Colorado. J. Soil Water Conserv. 57:121-126.

Bradford, M.A., T.H. Jones, R.D. Bardgett, H.I.J. Black, B. Boag, M. Bonkowski, R. Cook, T. Eggers, A.C. Gange, S.J. Grayson, E. Kandeler, A.E. McCaig, J.E. Newington, J.I. Prosser, H. Setala, P.L. Staddon, G.M. Tordoff, D. Tscherko, and J.H. Lawton. 2002. Impacts of soil faunal community composition on model grassland ecosystems. Science 298:615-618.

Brady, N.C., and R.R. Weil. 2002. The Nature and Properties of Soils. Thirteenth edition. Prentice Hall. Upper Saddle River, New Jersey.

Brinsfield, R., K. Staver, and W. Magette. 1988. The role of cover crops in reducing nitrate leaching to groundwater. p. 127-146. *In* Agricultural impacts on groundwater. National Well Water Assoc., Dublin, OH.

Bruce, R.R., G.W. Langdale, L.T. West, and W.P. Miller. 1995. Surface soil degradation and soil productivity restoration and maintenance. Soil Sci. Soc. of Am. J. 59:654-660.

Buyanovsky, G.A., M. Aslam and G.H. Wagner. 1994. Carbon turnover in soil physical fractions. Soil Sci. Soc. Am. J. 58:1167-1173.

Cambardella, C.A., and E.T. Elliot, 1992. Particulate soil organic matter changes across a grassland cultivation sequence. Soil Sci. Soc. Am. J. 56:777-783.

Cambardella, C.A., and E.T. Elliot, 1993a. Methods for physical separation and characterization of soil organic matter fractions**.** Geoderma 56:449-457.

Cambardella, C.A., and E.T. Elliot, 1993b. Carbon and nitrogen distribution in aggregates from cultivated and native grassland soils. Soil Sci. Soc. Am. J. 57:1071-1076.

Campbell, C.A., V.O. Biederbeck, .G. McConkey, D. Curtin, and R. P. Zentner. 1999. Soil quality – Effects of tillage and fallow frequency. Soil organic matter quality as influenced by tillage and fallow frequency in a silt lom in southwester Saskatchewan. Soil Biol. Biochem. 31:1-7.

Carter, M.R, S.S. Andrews, and L.E. Drinkwater. 2004. Systems approaches for improving soil quality. p. 261-281. *In* P. Schjonning, S. Elmholt, and B.T. Christensen (ed.) Managing Soil Quality: Challenges in modern agiculture. CABI Publishing, Oxon, United Kingdom.

Chenu, C. 1995. Extracellular polysaccharides: An interface between microorganisms and soil constituents. p. 217. *In* P.M. Huang, J. Berthelin, J.-M. Bollag, W.B. McGill (Ed.) Environmental impact of soil component interactions: Land quality, natural and anthropogenic organics, Vol. 1. CRC Press, Boca Raton, FL.

Cheshire, M.V., A. Lomax, and C.M. Mundie. 1989. Structure of soil carbohydrates resistant to periodate oxidation. J. Soil. Sci. 40:865-872.

Christensen, B.T. 1992. Physical fractionation of soil and organic matter in primary particle size and density separates. p. 1-90. *In* Advances in soil science, Vol. 20. Springer-Verlag, New York.

Christensen, B.T. and A.E. Johnston. 1997. Soil organic matter and soil quality: Lessons learned from long-term experiments at Askov and Rothamsted. p. 399-430. *In* E.G. Gregorich and M.R. Carter (ed.) Soil quality for crop production and ecosystem health. Elsevier Science Publishers B.V., Amsterdam, The Netherlands.

Chromec, F.W. and F.R. Magdoff. 1984. Alternative methods fore using organic materials: composting vs. adding directly to soil. J. Environ. Sci. Hlth. 19:697-711.

Cotton, F.A., and G. Wilkinson. 1965. Advanced inorganic chemistry. 4th ed. Interscience Publishers, John Wiley and Sons, New York. p. 839-840.

CTIC. 1998. 17th Annual Crop Residue Management Survey Report. Conservation Technology Information Center, West Lafayette, IN, USA.

Dalal, R.C., and R.J. Henry. 1988. Cultivation effects on carbohydrate contents of soil and soil fractions. Soil Sci. Soc. Am. J. 52:1361-1365.

Dao, T.H., J.H. Stiegler, J.C. Banks, L.B. Boerngen, and B. Adams. 2002. Post-contract land use effects on soil carbon and nitrogen in conservation reserve grassland. Agron J. 94:146-152.

Davidson E.A., L.F. Galloway, and M.K. Strand. 1987. Assessing soil available carbon: Comparison of techniques across selected forest soils. Comm. Soil Sci. Plant Anal. 18:45-64.

DeLuca, T.H., and D.R. Keeney. 1994. Soluble carbon and nitrogen pools of prairie and cultivated soils: Seasonal variation. Soil Sci. Soc. Am. J. 58:835-840.

Díaz-Zorita, M., D.E. Buschiazzo, and N. Peinemann. 1999. Soil organic matter and wheat productivity in the semiarid Argentine Pampas. Agron. J. 91:276-279.

Dick, W.A. 1983. Organic carbon, nitrogen, and phosphorus concentrations and pH in soil profiles as affected by tillage intensity. Soil Sci Soc, Am. J. 47:102-107.

Dick, W.A., E.L. McCoy, W.M. Edwards, and R. Lal. 1991. Continuous application of no-tillage to Ohio soils. Agron J. 83:65-73.

Dick, W.A., and E.G. Gregorich. 2004. Developing and maintaining soil organic matter levels. p. 103-120. *In* P. Schjonning, S. Elmholt, and B.T. Christensen (ed.) Managing Soil Quality: Challenges in modern agiculture. CABI Publishing, Oxon, United Kingdom.

Doran, J.W. 1987. Microbial biomass and mineralizable nitrogen distributions in no-till and plowed soils. Biol. Fertil. Soils 5:68-75.

Doran, J.W., and T.B. Parkin. 1994. Defining and assessing soil quality. p. 3-21. *In* J.W.Doran, D.C. Coleman, D.F. Bezdicek, and B.A. Stewart (ed.) Defining soil quality for a sustainable environment. SSSA Spec. Publ. 35. SSSA, Madison, WI.

Doran J.W., and M.R. Zeiss. 2000. Soil health and sustainability: Managing the biotic component of soil quality. Appl. Soil Ecol. 15:3-11.

Doran J.W. 2002. Soil health and global sustainability: Translating science into practice. Agric. Ecosyst. Environ. 88:119-127.

Dormaar, J.R. 1983. Chemical properties of soil and water-stable aggregates after sixty yeas of cropping to spring wheat. Plant Soil 75:51-61.

Duxbury, J.M., M.S. Smith, and J.W. Doran. 1989. Soil organic matter as a source and sink of plant nutrients. p. 33-67. *In* D.C. Coleman, J.M. Oades, and G. Uehara (ed.) Dynamics of soil organic matter in tropical ecosystems. NifTAL Project, Dept. of Agronomy and Soil Science, College of Tropical Agriculture and Human Resources, University of Hawaii, Honolulu, HI.

Eckert, D.J. 1988. Rye cover crops for no-tillage corn and soybean production. J. Prod. Agric. 1:207-210.

Ellert, B.H. and J.R. Bettany. 1990. Calculation of organic matter and nutrients stored in soils under contrasting management regimes. Can. J. Soil Sci. 75:529-538.

Elliot, E.T., 1986. Aggregate structure and carbon, nirtrogen, and phosphorus in native and cultivated soils. Soil Sci. Soc. Am. J. 50:627-633.

Franzluebbers, A.J., F.M. Hons, and V.A. Saladino. 1995. Sorghum, wheat, and soybean production as affected by long-term tillage, crop sequence, and N fertilization. Plant Soil 173:55-65.

Franzluebbers, A.J., and M.A. Arshad. 1996. Soil organic matter pools during early adoption of conservation tillage in Northwestern Canada. Soil Sci. Soc. Am. J. 60:1422-1427.

Franzluebbers, A. J., J.A. Stuedemann, H.H. Schomberg,and S.R. Wilkinson. 2000. Soil organic C and N pools under long-term pasture management in the Southern Piedmont USA. Soil Biol. Biochem. 32:469-478.

Franzluebbers, A. J., and J.A. Stuedemann. 2002. Particulate and non-particulate fractions of soil organic carbon under pastures in the Southern Piedmont USA. Environ. Pollution 116(Suppl. 1):S53-S62.

Franzluebbers, A.J. 2004. Tillage and residue management effects on soil organic matter. p. 227-268. *In* F. Magdoff and R.R. Weil (ed.) Soil organic matter in sustainable agriculture. CRC Press. Boca Raton, FL.

Gale, W.J. and C.A. Cambardella. 2000. Carbon dynamics of surface residue- and root-derived organic matter under simulated no-till. Soil Sci. Soc. Am. J. 64:190-195.

Greer, K.J. and J.J. Schoenau. 1997. Toward a framework for soil quality assessment and prediction. p. 313-321. *In* E.G. Gregorich and M.R. Carter (ed.) Soil quality for crop production and ecosystem health. Elsevier Science Publishers B.V., Amsterdam, The Netherlands.

Gregorich, E.G., M.R. Carter, D.A. Angers, C.M. Monreal, and B.H. Ellert. 1994. Towards a minimum data set to assess soil organic matter quality in agricultural soils. Can. J. Soil Sci. 74:367-385.

Gregorich, E.G., K.J. Greer, D.W. Anderson, and B.C. Liang. 1998. Carbon distribution and losses: Erosion and deposition effects. Soil Tillage Res. 47:291-302.

Guggenberger, G., S.D. Frey, J. Six, K. Paustian, and E.T. Elliot. 1999. Bacterial and fungal cell-wall residues in conventional and no-tillage agroecosystems. Soil Sci. Soc. Am. J. 63:1188-1198.

Guggenberger, G., and W. Zech. 1999. Soil organic matter composition under primary forest, pasture, and secondary forest succession, Region Huetar Norte, Costa Rica. For. Ecol. Manage. 124:93-104.

Gunapala, N., and K.M. Scow. 1998. Dynamics of soil microbial biomass and activity in conventional and organic farming systems. Soil Biol. Biochem. 30:805-816.

Gupta V.V.S.R., and J.J. Germida. 1988. Distribution of microbial biomass and its activity in different soil aggregate size classes as affected by cultivation. Soil Biol. Biochem. 20:777-786.

Haynes, R.J. 1999. Labile organic matter fractions and aggregate staability under short term, grass based leys. Soil Biol. Biochem. 31:1821-1830.

Haynes, R.J. 2000. Labile organic matter as an indicator of organic matter quality in arable and pastoral soils in New Zealand. Soil Biol. Biochem. 32:211-219.

Heil, D., and G Sposito. 1997. Chemcal attributes and processes affecting soil quality. p. 59-70. *In* E.G. Gregorich and M.R. Carter (ed.) Soil quality for crop production and ecosystem health. Elsevier Science Publishers B.V., Amsterdam, The Netherlands.

Hermawan, B., and A.A. Bomke. 1997. Effects of winter cover crops and successive spring tillage on soil aggregation. Soil Tillage Res. 44:109-120.

Herrick, J.E.. 2000. Soil quality: An indicator of sustainable land management? Appl. Soil Ecol. 15:75-83.

Houghton, R.A., J.E. Hobbie, J.E. Melillo, B. Moore, B.J. Peterson, G.R. Shaver, and G.M. Woodwell. 1983. Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: A new release of CO_2 to the atmosphere. Ecol. Monogr. 53:235-262.

Hsieh, Y.-P. 1992. Pool size and mean age of stable organic carbon in cropland. Soil Sci. Soc. Am. J. 56:460-464.

Hussain, I., K.R. Olson, and S.A. Ebelhar. 1999. Long-term tillage effects on soil chemical properties and organic matter fractions. Soil Sci. Soc. Am. J. 63:1335-1341.

Hu, S., N.J. Grunwald, A.H.C. van Bruggen, G.R. Gamble, L.E. Drinkwater, C Shennan, and M.W. Demment. 1997. Short-term effects of cover crop incorporation on soil carbon pools and nitrgen availability. Soil Sci. Soc. Am. J. 61:901-911.

Islam, K.R., and R.R. Weil. 1998. Microwave irradiation of soil for routine measurement of microbial biomass carbon. Biol.Fertil. Soils. 27:408-416.

Islam, K.R. and R.R. Weil. 2000. Soil quality indicator properties in mid-Atlantic soils as influenced by conservation management. J. Soil Water Conserv. 55:69-78.

Janzen, H.H., C.A. Campbell, B.H. Ellert, and E. Brremer. 1997. Soil organic matter dynamics and their relationship to soil quality. p. 277-291. *In* E.G. Gregorich and M.R. Carter (ed.) Soil quality for crop production and ecosystem health. Elsevier Science Publishers B.V., Amsterdam, The Netherlands.

Janzen, H.H. C.A. Campbell, E.G. Gregorich, and B.H. Ellert. 1998. Soil carbon dynamics in Canadian agroecosystems. p. 57-80. In R. Lal, J. Kimble, R.F. Follet, and B.A. Stewart (ed.) Soil processes and the carbon cycle. CRC Press, Boca Raton, FL.

Jenkinson, D.S. and D.S. Powlson. 1976. The effects of treatments on metabolism in soil. V. A method formeasuring soil biomass. Soil Biol. Biochem. 8:209-213.

Jenkinson, D.S., and J.H. Rayner. 1977. The turnover of soil organic matter in some of the Rothamsted classical experiments. Soil Sci. 123:298-305.

Jenkinson, D.S., and J.N. Ladd. 1981. Microbial biomass in soil: Measurement and turnover. p. 415-471. *In* E.A. Paul and J.N. Ladd (ed.) Soil Biochemistry. Vol. 5. Marcel Dekker, New York.

Jenkinson, D.S. 1988. Determination of microbial biomass carbon and nitrogen in soil. p. 368-386. *In* J.R. Wilson (ed.) Advances in nitrogen cycling in agricultural ecosystems. CABI Publishing, Oxon, England

Jordan, D., R.J. Kremer, W.A. Bergfield, K.Y. Kim, and V.N. Cacino. 1995. Rangeland soil carbon and nitrogen responses to grazing. J. Soil Water Conserv. 50:294-298.

Kabir, Z. and R.T. Koide. 2002. Effect of autumn and winter mycorerhizal cover crops on soil properties, nutrient uptake and yield of sweet corn in Pensylvania, USA. Plant Soil 238:205-215.

Karlen, D.L., N.S. Eash, and P.W.Unger. 1992. Soil and crop management effects on soil quality indicators. Am J. Altern. Agric. 7:48-55.

Karlen, D.L., N.C. Wollenhaupt, D.C. Erbach, E.C. Berry, J.B. Swan, N.S. Eash, and J.L. Jordahl. 1994a. Long-term tillage effects on soil quality. Soil Tillage Res. 32:313-327.

Karlen, D.L., G.E. Varvel, D.G. Bullock, and R.M. Cruse. 1994b. Crop rotations for the 21st century. Adv. Agron. 53:1-45.

Karlen, D.L., and C.A. Cambardella. 1996. Conservation strategies for improving soil quality and organic matter storage. p. 395-420. *In* M.R. Carter, and B.A. Stewart (ed.) Structure and organic matter storage in agricultural soils. CRC Press, Boca Raton, FL.

Karlen, D.L., S.S. Anderws, and J.W. Doran. 2001. Soil quality: Current Concepts and Applications. Adv. Agron. 74:1-40.

Karlen, D.L., M.J. Mausbach, J.W. Doran, R.G. Cline, R.F. Harris, and G.E. Schuman. 1997. Soil quality: A concept, definition, and framework for evaluation. Soil Sci. Soc. Am. J. 61:4-10.

Kennedy, A.C., and R.I. Papendick. 1995. Microbial characteristics of soil quality. J. Soil Water Conserv. 50:243-248.

Kessavalou, A., and D.T. Walters. 1997. Winter rye as a cover crop following soybean under conservation tillage. Agron. J. 89:68-74.

Khanna, P.K., B. Ludwig, J. Bauhaus, and C. O'Hara. 2001. Assessment and significance of labile C pools in forest soils. p. 167-182. *In* R. Lal, J.M. Kimble, R.F. Follett, and B.A. Stewart (ed.) Assessment methods for soil carbon. Lewis Publishers, Boca Raton, FL.

Kravchenko, A.N., and D.G. Bullock. 2000. Correlation of corn and soybean grain yield with topography and soil properties. Agron. J. 92:75-83.

Kuo, S., Sainju, U.M., and E.J. Jellum. 1997. Winter cover crop efects on soil organic carbon and carbohydrate in soil. Soil Sci. Soc. Am. J. 61:145-152.

Lal, R. 1998a. Basic concepts and global issues: Soil quality and agricultural sustainability. p. 3-12. *In* R. Lal (ed.) Soil quality and agricultural sustainability. Ann Arbor Press, Chelsea, MI.

Lal, R., J. Kimble, R. Follett, and C.V. Cole, 1998b. Potential of U.S. Cropland for Carbon Sequestration and Greenhouse Effect Mitigation. Sleeping Bear Press, Chelsea, MI, USA.

Lal, R., J.M. Kimble, and R.F. Follett. 2001. Methodological challenges toward balancing soil C pool and fluxes. p. 659-668. *In* R. Lal, J.M. Kimble, R.F. Follett, and B.A. Stewart (ed.) Assessment methods for soil carbon. Lewis Publishers, Boca Raton, FL.

Lal, R, T.M. Sobecki, T. Iivari, and J.M. Kimble. 2004. Soil degradation in the United States: Extent, Severity, and Trends. Lewis Publishers, Boca Raton, FL.

Larson W.E., and F.J. Pierce. 1991. Conservation and enhancement of soil quality evaluation for sustainable land management in the developing world. p. 175-203. *In* Evaluation for sustainable land management in the developing world. Int. Board Soil Res. and Management (IBSRAM). Proc. 12 (Vol. 2). Bangkok, Thailand.

Larson W.E., and F.J. Pierce. 1994. The dynamics of soil quality as aa measure of sustainable management. p. 37-51. *In* J.W.Doran, D.C. Coleman, D.F. Bezdicek, and B.A. Stewart (ed.) Defining soil quality for a sustainable environment. SSSA Spec. Publ. 35. SSSA, Madison, WI.

Lefroy, R.D.B, G.J. Blair, and W.M. Strong. 1993. Changes in soil organic matter as measured by organic carbon fractions and ^{13}C isotope abundance. Plant Soil 155/156:399-402.

Liebig, M. and J Doran. 1999. Evaluation of farmer's perceptions of soil quality indicators. Am. J. Altern. Agric. 14:11-21.

Liang, B.C., A.F. Mackenzie, M. Schnitzer, C.M. Monreal, P.R. Voroney, and R.P. Beyaert. 1998. Management-induced change in labile soil organic matter under continuous corn in eastern Canadian soils. Biol. Fertil. Soils 26:88-94.

Loginow, W., W. Wisniewski, S.S. Gonet, and B. Ciescinska. 1987. Fractionation of organic carbon based on susceptibility to oxidation. Polish J. Soil Sci. 20:47-52.

Loveland, P., and J. Webb. 2003. Is there a critical level of organic matter in agricultural soils of temperate regions: A review. Soil Tillage Res. 70:1-18.

Maddonni, G.A., S. Urricariet, C.M. Ghersa, and R.S. Lavado. 1999. Assessing soil quality in the Rolling Pampa, using soil properties and maize characteristics. Agron. J. 91:280-287.

Magdoff, F. 1992. Building soils for better crops: Organic matter management. Univ. of Nebraska Press, Lincoln, NE.

Magdoff, F. 1996. Soil organic matter fractions and implications for interpreting soil organic matter tests. p. 11-19. *In* F.R. Magdoff, M.A. Tabatabai, and E.A. Hanlon, Jr. (ed.) Soil organic matter: Analysis and interpretation. SSSA Spec. Publ. 46. SSSA, Madison, WI.

Magdoff, F., and R.R. Weil. 2004. Soil organic matter management strategies. p. 45-65. *In* F. Magdoff and R.R. Weil (ed.) Soil organic matter in sustainable agriculture. CRC Press. Boca Raton, FL.

Majchrzak, R.N., K.N. Olson, G. Bollero, and E.D. Nafziger. 2001. Using soil properties to predict wheat yields on Illinois soils. Soil Sci. 166:267-280.

Marumoto, T., J.P. Anderson, and K.H. Domsch. 1982. Mineralization of nutrients from soil microbial biomass. Soil Biol. Biochem. 14:469 475.

Martens, D.A., and W.T. Frankenberger, Jr. 1992. Decomposition of bacterial polymers in soil and their influence on soil structure. Biol. Fertil. Soils 13:65-73.

McCracken, D.V., S.J. Corak, M.S. Smith, W.W. Frye, and R.L.Blevins. 1989. Residual effects of nitrogen fertilization and winter cover cropping on nitrogen availability. Soil Sci. Soc. Am. J. 53:1459-1464.

McGill, W.B., H.W. Hunt, R.G. Woodmansee, and J.O. Reuss. 1981. PHOENIX, a model of the dynamics of carbon and nitrogen in grassland soils. Ecol. Bull. (Stockholm) 33:49-115.

McGill, W.B., K.R. Cannon, J.A. Robertson, and F.D. Cook. 1986. Dynamics of soil microbial biomass and water soluble C in Breton L after 50 years of cropping to two rotations. Can. J. Soil Sci. 66:1-19.

Melsted, S.W. 1954. New concepts of management of Corn Belt soils. Adv. Agron. 6:121-142.

Mendes, I.C., A.K. Bandick, R.P. Dick, and P.J. Bottomley. 1999. Microbial biomass and activities in soil aggregates affected by winter cover crops. Soil Sci. Soc. Am. J. 63:873-881.

Monreal, C.M., R.P. Zentner, and J.A. Robertson. An analysis of soil organic matter dynamics in relation to management, erosion and yield of wheat in long term crop rotation plots. Can. J. Soil Sci. 77:553-563.

Moody, P.W., S.A. Yo, and R.L. Aitken. 1997. Soil organic carbon, permanganate fractions, and the chemical properties of acidic soils. Aust. J. Soil Res. 35:1301-1308.

Morin, J., and J. van Winkel. 1996. The effect of raindrop impact and sheet erosion on infiltration ate and crust formation. Soil Sci. Soc. Am. J. 60:1223-1227.

N'Dayegamiye, A., and T.S. Tran. 2001. Effects of green manures on soil organic matter and wheat yields and N nutrition. Can. J. Soil Sci. 81:371-382.

Ndiaye, E.L., Sandeno, J.M., McGrath, D. and R.P. Dick. 2000. Integrative biological indicators for detecting change in soil quality. Am. J. Alt. Agric. 15:26-36.

Needelman, B.A., M.M. Wander, G.A. Bollero, C.W. Boast, G.K. Sims, and D.G. Bullock. 1999. Interaction of tillage and soil texture: Biologically active soil organic matter in Illinois. Soil Sci. Soc. Am. J. 63:1326-1334.

Oades, J.M. 1984. Soil organic matter and structural stability: Mechanisms and implications for management. Plant Soil 76:319-337.

Odland, T.E., and H.C. Knoblauch. 1938. The value of cover crops in continuous corn culture. J. Am. Soc. Agron. 30:22-29.

Ortega, R.A. G.A. Peterson, and D.G. Westfall. 2002. Residue accumulationand changes in soil organic matter as affected by cropping intensity in no-till dryland agroecosystems. Agron J. 94:944-954.

Pagliai, M., and L.V. Antisari. 1993. Influence of waste organic matter on soil micro- and macrostructure. Bioresource Tech. 43:205-213.

Parr J.F., R.I. Papendick, S.B. Hornik, and R.E. Meyer. 1992. Soil quality: Attributes and relationship to alternative and sustainable agriculture. Am. J. Alt. Agric. 7:5-10.

Parton, W.J., D.S. Schimel, C.V. Cole, and D.S. Ojima. 1987. Analysis of Factors Controlling Soil Organic Matter Levels in Great Plains Grasslands. Soil Sci. Soc. Am. J. 51:1173-1179.

Parton W.J., and P.E. Rasmussen. 1994. Long term effects of crop management in wheat-fallow: II. CENTURY model simulations. Soil Sci. Soc. Am. J. 58:530-536.

Paul, E.A., and J. Van Veen. 1978. The use of tracers to determine the dynamic nature of organic matter. Trans. Int. Congr. Soil Sci., 11th 3:61-102.

Paul, E.A. 1984. Dynamics of organic matter in soils. Plant Soil 76:275-285.

Paustian, K., W.J. Parton, and J. Persson. 1992. Modeling soil organic matter in organic-amended and nitrogen-fertilized long term plots. Soil Sci. Soc. Am. J. 56:476-488.

Paustian, K. H.P. Collins, and E.A. Paul. 1997a. Management controls on soil carbon. p. 15-49. *In* E.A. Paul, K. Paustian, E.T. Elliot, and C.V. Cole (ed.) Soil organic matter in temperate agroecosystems. CRC Press, Boca Raton, FL.

Paustian, K., O. Amdren, H.H. Janzen, R. Lal, P. Smith, G. Tian, H. Tiesssen, M. Van Noordwijk, and P.L. Woomer. 1997b. Agricultural soils as a sink to mitigate CO_2 emissions. Soil Use Manage. 13:230-244.

Pieri, C.J.M.G. 1992. Fertility of soils: A future for farming in the West African Savannah. Springer-Verlag, Berlin.

Potter, K.N., H.A. Tolbert, O.R. Jones, J.E. Matocha, J.E. Morrison, and P.W. Unger. 1998. Distributionan amount of soil organic C in long-term management systems in Texas. Soil Tillage Res. 47:309-321.

Puget, P. and L.E. Drinkwater. 2001. Short-term dynamics of root and shoot derived carbon from a leguminous green manure. Soil Sci. Soc. Am. J. 65:771-779.

Pulleman, M.M., J Bouma, E.A. van Essen, and E.W. Meijles. 2000. Soil organic matter content as a function of different land use history. Soil Sci. Soc. Am. J. 64:689-693.

Raimbault, B.A., T.J. Vyn, and M. Tollenaar. 1990. Corn Response to rye cover crop management and spring tillage systems. Agron. J. 82:1088-1093.

Raimbault, B.A., T.J. Vyn, and M. Tollenaar. 1991. Corn response to rye cover crop, tillage methods, and planter options. Agron. J. 83:287-290.

Rasiah, V., and B.D. Kay. 1995. Runoff and soil loss as influenced by selected stability parameters and cropping and tillage practices. Geoderma 68:321-329.

Rasmussen, P.E., and W.J. Parton. 1994. Long-term effects of residue management in wheat-fallow: I. Inputs, yield, and soil organic matter. Soil Sci. Soc. Am. J. 58:523-530.

Römkens, P.F.A.M., J. van der Plicht, and J. Hassink. 1999. Soil organic matter dynamics after the conversion of arable land to pasture. Biol. Fertil. Soils 28:277-284.

Ruttan, V.W. 1999. The transition to agricultural sustainability. Proc. National Acad. Sci. 96:5960-5967.

Sainju, U.M., B.P. Singh, and W.F. Whitehead. 2000. Cover crops and nitrogen fertilization effects on soil carbon and nitrogen and tomato yield. Can. J. Soil Sci. 80:523-532.

Sainju, U.M., B.P. Singh, and W.F. Whitehead. 2001. Comparison of the effects of cover crops and nitrogen fertilization on tomato yield, root growth and soil properties. Scientia Horticulturae 91:2001-214.

Salinas-Garcia, J.R., F.M. Hons, and J.E. Matocha. 1997. Long-term effects of tillage and fertilization on soil organic matter dynamics. Soil Sci. Soc. Am. J. 61:152-159.

Seybold, C.A., M.J. Mausbach, D.L. Karlen, and H.H. Rogers. 1996. Quantification of soil quality. p.53-68. *In* T.S.Q. Intitute (ed.) The soil quality concept. USDA/NRCS, Washington, D.C.

Shang, C., and H. Tiessen. 1997. Organic matter lability in tropical Oxisol: Evidence from shifting cultivation, chemical oxidation, particle size, and magnetic fractionations. Soil Sci. 162:795-807.

Sikora, L.J., and D.E. Stott. 1996. Soil Organic Carbon and Nitrogen. p. 157-167. *In* J.W.Doran and A.J. Jones (ed.) Methods for assessing soil quality. SSSA Spec. Publ. 35. SSSA, Madison, WI.

Six, J., K. Paustian, E.T. Elliot, and C. Combrink. 2000. Soil structure and organic matter: I. Distribution of aggregate size classes and aggregate-associated carbon. Soil Sci. Soc. Am. J. 64:681-689.

Six, J., R.T. Conant, E.A. Paul, and K. Paustian. 2002. Stabilization mechanisms of soil orgainc matter: implications for C-saturation of soils. Plant Soil 241:155-176.

Skoog, D.A., and D.M. West. 1969. Applications of oxidation-reduction reagents to volumetric organic analysis. Chapter 21. *In* Fundamentals of Analytical Chemistry. 2nd Edition. Holt, Rinehart, and Winston, New York, NY.

Smith, M.S., W.W. Frye, and J.J. Varco. 1987. Legume winter cover crops. Adv Soil Sci. 7:95-139.

Sparling, G., M. Vojvodić-Vuković, and L.A Schipper. 1998. Hot-water-soluble C as a simple measure of labile soil organic matter: the relationship with microbial biomass C. Soil Biol. Biochem. 30:1469-1472.

Soil Science Society of America. 2001. Internet glossary of soil science terms [Online]. Available by the Soil Science Society of America at www.soils.org/sssagloss, accessed 15 June 2004.

Stanford, G. 1978. Evaluation of ammonium release by alkaline ammonium extraction as an index of soil nitrogen availability. Soil Sci. 126:244-253.

Stanier, R.Y., M. Doudoroff, and E.A. Adelberg. 1968. General microbiology. MacMillan, London.

Staver, K.W. and R.B. Brinsfield. 1990. Patternsof soil nitrate availability in corn production systems: Implications for reducing groundwater contamination. J. Soil Water Conserv. 45:318-323.

Steer, A. 1998. Making development sustainable. Adv. Geo-Ecol. 31:857-865.

Stevenson, F.J., and M.A. Cole. 1999. Cycles of soil: Carbon, nitrogen, phosphorus, sulphur, micronutrients. John Wiley & Sons Inc., New York.

Stine, M.A., and R.R. Weil. 2002. The relationship between soil quality and crop productivity across three tillagesystems in south central Honduras. Am. J. Altern. Agric. 17:2-8.

Strickling, E. 1975. Crop sequences and tillage in efficient crop production. p. 20-29 *In* Agron. Abstr. American Society of Agronomy, Madison, WI.

Studdert, G.A., and H.E. Echeverría. 2000. Crop rotations and nitrogen fertilization to manage soil organic carbon dynamics. Soil Sci. Soc. Am. J. 64:1496-1503.

Studdert, G.A., H.E. Echeverria, and E.M. Casanovas. 1997. Crop-pasture rotation for sustaining the quality and productivity of a Typic Argiudoll. Soil Sci. Soc. Am. J. 61:1466-1472.

Syers, J.K., and E.T. Craswell. 1995. Role of soil organic matter in sustainable agricultural systems. p. 7-14. *In* R.D.B. Lefroy, G.J. Blair, and E.T. Craswell (ed.) Soil organic matter management for sustainable agriculture: A workshop held in Ubon, Thailand, 24-26 August 1994. ACIAR Proceedings No. 56, Australian Center for International Research, Canberra, Australia.

Tabatabai, M.A. 1996. Soil organic matter testing: An overview. p. 1-9. *In* F.R. Magdoff, M.A. Tabatabai, and E.A. Hanlon, Jr. (ed.) Soil organic matter: Analysis and interpretation. SSSA Spec. Publ. 46. SSSA, Madison, WI.

Tiessen, H., E. Cuevas, and P. Chacon. 1994. The role of soil organic matter in sustaining soil fertility. Nature 371:783-785.

Tirol-Padre, A., and J.K. Ladha. 2004. Assessing the reliability of permanganate-oxidizable carbon as an index of soil labile carbon. Soil Sci. Soc. Am. J. 68:969-978.

Tisdall, J.M., and J.M. Oades. 1982. Organic matter and water stable aggregates in soils. J. Soil Sci. 33:141-163.

Torbert, H.A., D.W. Reeves, and R.L. Mulvaney. Winter legume cover crop benefits to corn: rotation vs. fixed-nitrogen effects. Agron J. 88:527-535.

Unger, P.W. 1982. Surface soil physical properties after 36 years of cropping to winter wheat. Soil Sci. Soc. Am. J. 46:796-801.

USDA-NRCS. 1998. Soil quality test kit guide. Soil Quality Institute, Natural resources Conservation Service, United States Department of Agriculture, Lincoln, NE and Washington DC.

Utomo, M., W.W. Frye, and R.L. Blevins. 1990. Sustaining soil nitrogen for corn using hairy vetch cover crop. Agron. J. 82:979-983.

Vance, E.D., P.C. Brookes, and D.S. Jenkinson. 1987. An extraction method for measuring soil microbial biomass C. Soil Biol. Biochem. 19:703-707.

Van Doren, D.M., Jr., Triplett, G.B., Jr., and J.E. Henry. 1976. Influence of long-term tillage, crop rotation, and soil type combinations on corn yields. Soil Sci. Soc. Am. J. 40:100-105.

Vaughan, J.D. and G.K. Evanylo, 1998. Corn response to cover crop species, spring desiccation time, and residue management. Agron. J. 90:536-544.

Wagger, M.G., M.L. Cabrera, and N.N. Rannels. 1998. Nitrogen and carbon cycling in relation to cover crop residue quality. Soil Water Cons. 53:214-224.

Walkley A., and I.A. Black. 1947. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Sci. 37:29-38.

Wander, M.M., S.J. Traina, B.R.Stinner, an S.E. Peters. 1994. Organic and conventional management effects on biologically active soil organic matter pools. Soil Sci. Soc. Am. J. 8:1130-1139.

Wander, M.M., M.G. Bidart, and S. Aref. 1998. Tillage impacts on depth distribution of total and particulate organic matter in three Illinois soils. Soil Sci. Soc. Am. J. 62:1704-1711.

Wander, M.M., and G.A. Bollero. 1999. Soil quality assessment of tillage impacts in Illinois. Soil Sci. Soc. Am. J. 63:961-971.

Wander, M.M., and L.E. Drinkwater. 2000. Fostering soil stewardship through soil quality assessment. Appl. Soil Ecol. 15:61-73.

Wander M.M., and X.M. Yang. 2000. Influence of tillage on the dynamics of loose- and occluded-particulate organic and humified organic matter fractions. Soil Biol. Biochem. 32:1151-1160.

Wander M.M. 2004. Soil organic matter fractions and their relevance to soil function. p. 67-102. *In* F. Magdoff and R.R. Weil (ed.) Soil organic matter in sustainable agriculture. CRC Press. Boca Raton, FL.

Warkentin, B.P. 1995. The changing concept of soil quality. J. Soil Water Conserv. 50:226-228.

Weil, R.R., K.A. Lowell, and H.M. Shade. 1993. Effects of intensity of agronomic practices on a soil ecosystem. Am. J. Altern. Agric. 8:5-14.

Weil, R.R., K.R. Islam, M.A. Stine, J.B. Gruver, and S.E. Samson-Liebig. 2003. Estimating active carbon for soil quality assessment: A simplified method for labd and feld use. Am. J. Altern. Agric. 18:3-17.

Weil, R.R., and F. Magdoff. 2004. Significance of soil organic matter to soil quality and health. p. 1-43. *In* F. Magdoff and R.R. Weil (ed.) Soil organic matter in sustainable agriculture. CRC Press. Boca Raton, FL.

Weinhold, B.J., and D.L. Tanaka. 2001. Soil property changes during conversion from perrenial vegetation to annual cropping. Soil Sci. Soc. Am. J. 65: 1795-1803.

Whitbread, A.M., G.J. Blair, and R.D.B. Lefroy. 2000. Managing legume leys, residues and fertilisers to enhance the sustainability of wheat cropping systems in Australia 2. Soil physical fertility and carbon. Soil Tillage Res. 54:77-89.

Wilson, D.O., and W.L. Hargrove. 1986. Release of nitrogen from crimson clover residue under two tillage systems. Soil Sci. Soc. Am. J. 50:1251-1254.

Wood, C.W., D.G. Westfall, and G.A. Peterson. 1991. Soil carbon and nitrogen changes on intiation of no-till cropping systems. Soil Sci. Soc. Am. J. 55:470-476.

Zsolnay, A., and H. Gorlitz. 1994. Water extractable soil organic matter in arable soils: Effects of drought and long-term fertilization. Soil Biol. Biochem. 26:1257-1261.

Chapter Two

Alvarez, C.R., R. Alvarez, M.S. Grigera, and R.S. Lavado. 1998b. Associations between organic matter fractions and the active soil microbial biomass. Soil Biol. and Biochem. 30:767-773.

Alvarez, R., C.R. Alvarez, and H.S. Steinbach. 2002. Association between soil organic matter and wheat yield in humid Pampa of Argentina. Comm. Soil Sci. Plant Anal. 33:749-757.

Arshad, M.A., and G.M. Coen. 1992. Characterization of soil quality: Physical and chemical criteria. Am. J. Altern. Agric. 7:25-31.

Banerjee, M.R., and S.J. Chapman. 1996. The significance of microbial biomass sulphur in soil. Biol. Fert. Soils 22:116-125.

Bauer, A., and A.L. Black. 1994. Quantification of the effect of soil organic matter content on soil productivity. Soil Sci. Soc. Am. J. 58:185-193.

Bauer, P.J., and W.J. Busscher, 1996. Winter cover and tillage influences on Coastal Plain cotton production. J. Product. Agric. 9:50-54.

Bell, M.J., P.W. Moody, S.A. Yo, and R.D. Connoly. 1999. Using active fractions of soil organic matter as indicators of the sustainability of Ferrosol farming systems. Aust. J. Soil Res. 37:279-287.

Biederbeck, V.O., H.H. Janzen, C.A. Campbell, R.P. Zentner. 1994. Labile soilorganic matter as influenced by cropping practices in an arid environment. Soil Biol. Biochem. 26:1647-1656.

Blevins, R.L., W.W. Frye, and M.S. Smith. 1985. The effects of conservation tillage on soil properties. p. 99-110. In F.M. D'Itri (ed.) A systems approach to conservation tillage. Lewis Publishers, Chelsea, MI.

Blevins, R.L., J.H. Herbeck, and W.W. Frye. 1990. Legume cover crops as a nitrogen source for no-till corn and grain sorghum. Agron. J. 82:769-772.

Blair, G.J., R.D.B. Lefroy, and L. Lisle. 1995. Soil carbon fractions based on their degree of oxidation and the development of a carbon management index for agricultural systems. Aust. J. Agric. Res. 46:1459-1466.

Bowman, R.A., and R.L. Anderson. 2002. Conservation Reserve Program: effects on soil organic carbon and preservation when converting back to cropland in northeastern Colorado. J. Soil Water Conserv. 57:121-126.

Brady, N.C., and R.R. Weil. 2002. The Nature and Properties of Soils. Thirteenth edition. Prentice Hall. Upper Saddle River, New Jersey.

Bruce, R.R., G.W. Langdale, L.T. West, and W.P. Miller. 1995. Surface soil degradation and soil productivity restoration and maintenance. Soil Sci. Soc. of Am. J. 59:654-660.

Cambardella, C.A., and E.T. Elliot, 1992. Particulate soil organic matter changes across a grassland cultivation sequence. Soil Sci. Soc. Am. J. 56:777-783.

Campbell, C.A., V.O. Biederbeck, .G. McConkey, D. Curtin, and R. P. Zentner. 1999. Soil quality – Effects of tillage and fallow frequency. Soil organic matter quality as influenced by tillage and fallow frequency in a silt lom in southwester Saskatchewan. Soil Biol. Biochem. 31:1-7.

Carter, M.R, S.S. Andrews, and L.E. Drinkwater. 2004. Systems approaches for improving soil quality. p. 261-281. *In* P. Schjonning, S. Elmholt, and B.T. Christensen (ed.) Managing Soil Quality: Challenges in modern agiculture. CABI Publishing, Oxon, United Kingdom.

Cox, F.R., and E. Uribe. 1992. Potassium in two humid tropical Ultisols under a corn and soybean cropping system. I. Management. Agron. J. 84:480-484.

Custer, B.H. 1985. Soil Survey, Lancaster County, Pennsylvania. United States. Soil Conservation Service. Washington, D.C.

DeLuca, T.H., and D.R. Keeney. 1994. Soluble carbon and nitrogen pools of prairie and cultivated soils: Seasonal variation. Soil Sci. Soc. Am. J. 58:835-840.

Díaz-Zorita, M., D.E. Buschiazzo, and N. Peinemann. 1999. Soil organic matter and wheat productivity in the semiarid Argentine Pampas. Agron. J. 91:276-279.

Dick, R.P. 1992. A review: long-term effects of agricultural systems on soil biochemical and microbial parameters. Agric. Ecosys. Environ. 40:25-36.

Dick, W.A. 1983. Organic carbon, nitrogen, and phosphorus concentrations and pH in soil profiles as affected by tillage intensity. Soil Sci Soc, Am. J. 47:102-107.

Dick, W.A., E.L. McCoy, W.M. Edwards, and R. Lal. 1991. Continuous application of no-tillage to Ohio soils. Agron J. 83:65-73.

Dick, W.A., and E.G. Gregorich. 2004. Developing and maintaining soil organic matter levels. p. 103-120. *In* P. Schjonning, S. Elmholt, and B.T. Christensen (ed.) Managing Soil Quality: Challenges in modern agiculture. CABI Publishing, Oxon, United Kingdom.

Eckert, D.J. 1988. Rye cover crops for no-tillage corn and soybean production. J. Prod. Agric. 1:207-210.

Ellert, B.H. and J.R. Bettany. 1990. Calculation of organic matter and nutrients stored in soils under contrasting management regimes. Can. J. Soil Sci. 75:529-538.

Gregorich, E.G., M.R. Carter, D.A. Angers, C.M. Monreal, and B.H. Ellert. 1994. Towards a minimum data set to assess soil organic matter quality in agricultural soils. Can. J. Soil Sci. 74:367-385.

Greer, K.J. and J.J. Schoenau. 1997. Toward a framework for soil quality assessment and prediction. p. 313-321. *In* E.G. Gregorich and M.R. Carter (ed.) Soil quality for crop production and ecosystem health. Elsevier Science Publishers B.V., Amsterdam, The Netherlands.

Gruver, J.B. 1999. Relationships between farmer perceptions of soil quality and management sensitive soil parameters. M.S. Thesis. University of Maryland, Colllege Park, MD.

Gunapala, N., and K.M. Scow. 1998. Dynamics of soil microbial biomass and activity in conventional and organic farming systems. Soil Biol. Biochem. 30:805-816.

Haby, V.A., M.P. Russelle, and E.O. Skogley. 1990. Testing soils for potassium calcium and magnesium. p. 181-227 *In* R.L. Westerman (ed.) Soil testing and plant analysis. 3rd edition. Soil Science Society of America, Madison, WI.

Hagerstown Weather Station. 2001. Past Weather Data & Graphs [Online]. Available at http://i4weather.net/ (Accessed 30 June 2004; verified 1 Aug. 2004). Hagerstown Weather Station, Hagerstown, MD.

Hagerstown Weather Station. 2002. Past Weather Data & Graphs [Online]. Available at http://i4weather.net/ (Accessed 30 June 2004; verified 1 Aug. 2004). Hagerstown Weather Station, Hagerstown, MD.

Hagerstown Weather Station. 2003. Past Weather Data & Graphs [Online]. Available at http://i4weather.net/ (Accessed 30 June 2004; verified 1 Aug. 2004). Hagerstown Weather Station, Hagerstown, MD.

Hermawan, B., and A.A. Bomke. 1997. Effects of winter cover crops and successive spring tillage on soil aggregation. Soil Tillage Res. 44:109-120.

Hurlbert, S.H. 1984. Pesudoreplication and the design of ecological field experiments. Ecol. Monogr. 54:187-211.

Hu, S., N.J. Grunwald, A.H.C. van Bruggen, G.R. Gamble, L.E. Drinkwater, C Shennan, and M.W. Demment. 1997. Short-term effects of cover crop incorporation on soil carbon pools and nitrgen availability. Soil Sci. Soc. Am. J. 61:901-911.

Islam, K.R. and R.R. Weil. 2000. Soil quality indicator properties in mid-Atlantic soils as influenced by conservation management. J. Soil Water Conserv. 55:69-78.

Jenkinson, D.S., and J.N. Ladd. 1981. Microbial biomass in soil: Measurement and turnover. p. 415-471. *In* E.A. Paul and J.N. Ladd (ed.) Soil Biochemistry. Vol. 5. Marcel Dekker, New York.

Jenkinson, D.S. 1988a. Determination of microbial biomass carbon and nitrogen in soil. p. 368-386. *In* J.R. Wilson (ed.) Advances in nitrogen cycling in agricultural ecosystems. CABI Publishing, Oxon, England

Jenkinson, D.S. 1988b. Soil organic matter and its dynamics. p. 564-607. *In* A. Wild (ed.) Russell's soil conditions and plant growth. 11th ed. Longman, New York.

Kabir, Z. and R.T. Koide. 2002. Effect of autumn and winter mycorerhizal cover crops on soil properties, nutrient uptake and yield of sweet corn in Pensylvania, USA. Plant Soil 238:205-215.

Kennedy, A.C., and R.I. Papendick. 1995. Microbial characteristics of soil quality. J. Soil Water Conserv. 50:243-248.

Kessavalou, A., and D.T. Walters. 1997. Winter rye as a cover crop following soybean under conservation tillage. Agron. J. 89:68-74.

Kirby, R.M., E.D. Matthews, and M.A.Bailey. 1967. Soil Survey, Prince George's County, Maryland. U.S. Dept. of Agriculture, Soil Conservation Service. Washington, D.C.

Kortleven, J. 1963. Quantitative aspects of humus accumulation and decomposition. Versl. Landb. Ond. nr. 69.1 PUDOC, Wageningen (in Dutch).

Kravchenko, A.N., and D.G. Bullock. 2000. Correlation of corn and soybean grain yield with topography and soil properties. Agron. J. 92:75-83.

Kuo, S., Sainju, U.M., and E.J. Jellum. 1997. Winter cover crop efects on soil organic carbon and carbohydrate in soil. Soil Sci. Soc. Am. J. 61:145-152.

Large, E.C. 1954. Growth stages in cereals. Illustration of the Feekes scale. Plant Pathol. 3:128-129.

Larson W.E., and F.J. Pierce. 1994. The dynamics of soil quality as a measure of sustainable management. p. 37-51. *In* J.W.Doran, D.C. Coleman, D.F. Bezdicek, and

B.A. Stewart (ed.) Defining soil quality for a sustainable environment. SSSA Spec. Publ. 35. SSSA, Madison, WI.

Lefroy, R.D.B, G.J. Blair, and W.M. Strong. 1993. Changes in soil organic matter as measured by organic carbon fractions and ^{13}C isotope abundance. Plant Soil 155/156:399-402.

Liebig, M.A. and J.W. Doran. 1999. Evaluation of farmers' perceptions of soil quality indicators. Am. J. Alt. Agric. 14:11-21.

Loveland, P., and J. Webb. 2003. Is there a critical level of organic matter in agricultural soils of temperate regions: A review. Soil Tillage Res. 70:1-18.

Maddonni, G.A., S. Urricariet, C.M. Ghersa, and R.S. Lavado. 1999. Assessing soil quality in the Rolling Pampa, using soil properties and maize characteristics. Agron. J. 91:280-287.

Majchrzak, R.N., K.N. Olson, G. Bollero, and E.D. Nafziger. 2001. Using soil properties to predict wheat yields on Illinois soils. Soil Sci. 166:267-280.

Marumoto, T., J.P. Anderson, and K.H. Domsch. 1982. Mineralization of nutrients from soil microbial biomass. Soil Biol. Biochem. 14:469 475.

Matthews, E.D. 1962. Soil survey, Washington County, Maryland. United States. Soil Conservation Service. U.S. Govt. Print. Off., Washington, D.C.

McCracken, D.V., S.J. Corak, M.S. Smith, W.W. Frye, and R.L.Blevins. 1989. Residual effects of nitrogen fertilization and winter cover cropping on nitrogen availability. Soil Sci. Soc. Am. J. 53:1459-1464.

Mendes, I.C., A.K. Bandick, R.P. Dick, and P.J. Bottomley. 1999. Microbial biomass and activities in soil aggregates affected by winter cover crops. Soil Sci. Soc. Am. J. 63:873-881.

Moody, P.W., S.A. Yo, and R.L. Aitken. 1997. Soil organic carbon, permanganate fractions, and the chemical properties of acidic soils. Aust. J. Soil Res. 35:1301-1308.

N'Dayegamiye, A., and T.S. Tran. 2001. Effects of green manures on soil organic matter and wheat yields and N nutrition. Can. J. Soil Sci. 81:371-382.

Ndiaye, E.L., Sandeno, J.M., McGrath, D. and R.P. Dick. 2000. Integrative biological indicators for detecting change in soil quality. Am. J. Alt. Agric. 15:26-36.

NOAA-NCDC. 2001. National Oceanic and Atmospheric Administration - National Climatic Data Center [Online]. Available at

www7.ncdc.noaa.gov/SerialPublications/index.html (Accessed 30 June 2004; verified 1 Aug. 2004). National Climatic Data Center, Asheville, NC.

NOAA-NCDC. 2002. National Oceanic and Atmospheric Administration - National Climatic Data Center [Online]. Available at www7.ncdc.noaa.gov/SerialPublications/index.html (Accessed 30 June 2004; verified 1 Aug. 2004). National Climatic Data Center, Asheville, NC.

NOAA-NCDC. 2003. National Oceanic and Atmospheric Administration - National Climatic Data Center [Online]. Available at www7.ncdc.noaa.gov/SerialPublications/index.html (Accessed 30 June 2004; verified 1 Aug. 2004). National Climatic Data Center, Asheville, NC.

Northeast Coordinating Committee on Soil Testing. 1995. Recommended soil testing procedures for the Northeastern United States. 2nd edition. Northeast regional publication No.493, Agricultural Experiment Station, University of Delaware, Newark, DE.

Odland, T.E., and H.C. Knoblauch. 1938. The value of cover crops in continuous corn culture. J. Am. Soc. Agron. 30:22-29.

Potter, K.N., H.A. Tolbert, O.R. Jones, J.E. Matocha, J.E. Morrison, and P.W. Unger. 1998. Distributionan amount of soil organic C in long-term management systems in Texas. Soil Tillage Res. 47:309-321.

Raimbault, B.A., T.J. Vyn, and M. Tollenaar. 1990. Corn Response to rye cover crop management and spring tillage systems. Agron. J. 82:1088-1093.

Sainju, U.M., B.P. Singh, and W.F. Whitehead. 2000. Cover crops and nitrogen fertilization effects on soil carbon and nitrogen and tomato yield. Can. J. Soil Sci. 80:523-532.

Sainju, U.M., B.P. Singh, and W.F. Whitehead. 2001. Comparison of the effects of cover crops and nitrogen fertilization on tomato yield, root growth and soil properties. Scientia Horticulturae 91:2001-214.

Salinas-Garcia, J.R., F.M. Hons, and J.E. Matocha. 1997. Long-term effects of tillage and fertilization on soil organic matter dynamics. Soil Sci. Soc. Am. J. 61:152-159.

Saviozzi, A., A. Biasci, R. Riffaldi, and R. Levi-Minzi. 1999. Long-term effects of farmyard manure and sewage sludge on some soil biochemical characteristics. Biol. Fert. Soil. 30:100-106.

Scharf, P.C. ; Quarles, D.B. ; Lory, J.A. 2000. Nitrogen response of no-till corn in first and second years following Conservation Reserve Program. Comm. soil sci. plant anal. 31:2501-2508.

Shang, C., and H. Tiessen. 1997. Organic matter lability in tropical Oxisol: Evidence from shifting cultivation, chemical oxidation, particle size, and magnetic fractionations. Soil Sci. 162:795-807.

Sikora, L.J., and D.E. Stott. 1996. Soil Organic Carbon and Nitrogen. p. 157-167. *In* J.W.Doran and A.J. Jones (ed.) Methods for assessing soil quality. SSSA Spec. Publ. 35. SSSA, Madison, WI.

Six, J., R.T. Conant, E.A. Paul, and K. Paustian. 2002. Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. Plant Soil 241:155-176.

Smith, M.S., W.W. Frye, and J.J. Varco. 1987. Legume winter cover crops. Adv Soil Sci. 7:95-139.

Stine, M.A., and R.R. Weil. 2002. The relationship between soil quality and crop productivity across three tillagesystems in south central Honduras. Am. J. Altern. Agric. 17:2-8.

Strickling, E. 1975. Crop sequences and tillage in efficient crop production. p. 20-29 *In* Agron. Abstr. American Society of Agronomy, Madison, WI.

Tabatabai, M.A., and J.M. Bremner. 1991. Automated instruments for determination of total carbon, nitrogen, and sulfur in soils by combustion techniques. p. 261-286. *In* K.A. Smith (ed.) Soil analysis: Modern instrumental techniques. 2nd ed. Dekker, New York.

Tiessen, H., E. Cuevas, and P. Chacon. 1994. The role of soil organic matter in sustaining soil fertility. Nature 371:783-785.

Tirol-Padre, A., and J.K. Ladha. 2004. Assessing the reliability of permanganate-oxidizable carbon as an index of soil labile carbon. Soil Sci. Soc. Am. J. 68:969-978.

Tisdall, J.M., and J.M. Oades. 1982. Organic matter and water stable aggregates in soils. J. Soil Sci. 33:141-163.

Torbert, H.A., D.W. Reeves, and R.L. Mulvaney. Winter legume cover crop benefits to corn: rotation vs. fixed-nitrogen effects. Agron J. 88:527-535.

USDA-NRCS. 2003. The soil quality test kit guide [Online]. Available at http://soils.usda.gov/sqi/soil_quality/assessment/kit2.html (Accessed 1 Oct. 2004; verified 25 Nov. 2004). Natural Resources Conservation Service and Agricultural Research Service, US Dept. of Agriculture, Lincoln, NE and Washington, DC.

Utomo, M., W.W. Frye, and R.L. Blevins. 1990. Sustaining soil nitrogen for corn using hairy vetch cover crop. Agron. J. 82:979-983.

Vaughan, J.D. and G.K. Evanylo, 1998. Corn response to cover crop species, spring desiccation time, and residue management. Agron. J. 90:536-544.

Wagger, M.G., M.L. Cabrera, and N.N. Ranells. 1998. Nitrogen and carbon cycling in relation to cover crop residue quality. J. Soil Water Conserv. 53:214-218.

Wander, M.M., S.J. Traina, B.R.Stinner, an S.E. Peters. 1994. Organic and conventional management effects on biologically active soil organic matter pools. Soil Sci. Soc. Am. J. 8:1130-1139.

Wander, M.M., and G.A. Bollero. 1999. Soil quality assessment of tillage impacts in Illinois. Soil Sci. Soc. Am. J. 63:961-971.

Wander, M.M., and M.G. Bidart. 2000. Tillage practice influences on the physical protection, bioavailability and composition of particulate organic matter. Biol. Fertil. Soils 32:360-367.

Wander, M.M., and L.E. Drinkwater. 2000. Fostering soil stewardship through soil quality assessment. Appl. Soil Ecol. 15:61-73.

Weil, R.R. 1992. Inside the heart of sustainable farming: an intimate look at soil life--and how to keep it thriving. The New Farm 14:48, 43, 45.

Weil, R.R., K.R. Islam, M.A. Stine, J.B. Gruver, and S.E. Samson-Liebig. 2003. Estimating active carbon for soil quality assessment: A simplified method for lab and field use. Am. J. Altern. Agric. 18:3-17.

Weil, R.R., and F. Magdoff. 2004. Significance of soil organic matter to soil quality and health. p. 1-43. *In* F. Magdoff and R.R. Weil (ed.) Soil organic matter in sustainable agriculture. CRC Press. Boca Raton, FL.

Chapter Three

Alvarez, C.R., R. Alvarez, M.S. Grigera, and R.S. Lavado. 1998. Associations between organic matter fractions and the active soil microbial biomass. Soil Biol. and Biochem. 30:767-773.

Anderson, J.P.E. 1982. Soil respiration. p. 837-871. In A.L. Page et al. (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Biederbeck, V.O., H.H. Janzen, C.A. Campbell, R.P. Zentner. 1994. Labile soil organic matter as influenced by cropping practices in an arid environment. Soil Biol. Biochem. 26:1647-1656

Blevins, R.L., W.W. Frye, and M.S. Smith. 1985. The effects of conservation tillage on soil properties. p. 99-110. In F.M. D'Itri (ed.) A systems approach to conservation tillage. Lewis Publishers, Chelsea, MI.

Blair, G.J., R.D.B. Lefroy, and L. Lisle. 1995. Soil carbon fractions based on their degree of oxidation and the development of a carbon management index for agricultural systems. Aust. J. Agric. Res. 46:1459-1466.

Cambardella, C.A., and E.T. Elliot, 1992. Particulate soil organic matter changes across a grassland cultivation sequence. Soil Sci. Soc. Am. J. 56:777-783.

Cambardella, C.A., and E.T. Elliot, 1993. Carbon and nitrogen distribution in aggregates from cultivated and native grassland soils. Soil Sci. Soc. Am. J. 57:1071-1076.

Cataldo, D.A., M Haroon, L.E. Schrader, and V.L. Young. 1975. Rapid colorimetric determination of nitrate in plant tissue by nitration of salicylic acid. Comm. Soil Sci. Plant Anal. 6:71-80.

Christensen, B.T. 1992. Physical fractionation of soil and organic matter in primary particle size and density separates. p. 1-90. *In* Advances in soil science, Vol. 20. Springer-Verlag, New York.

DeLuca, T.H., and D.R. Keeney. 1994. Soluble carbon and nitrogen pools of prairie and cultivated soils: Seasonal variation. Soil Sci. Soc. Am. J. 58:835-840.

Dick, R.P. 1992. A review: long-term effects of agricultural systems on soil biochemical and microbial parameters. Agric. Ecosys. Environ. 40:25-36.

Dick, W.A. 1983. Organic carbon, nitrogen, and phosphorus concentrations and pH in soil profiles as affected by tillage intensity. Soil Sci Soc, Am. J. 47:102-107.

Dick, W.A., E.L. McCoy, W.M. Edwards, and R. Lal. 1991. Continuous application of no-tillage to Ohio soils. Agron J. 83:65-73.

Dick, W.A., and E.G. Gregorich. 2004. Developing and maintaining soil organic matter levels. p. 103-120. *In* P. Schjonning, S. Elmholt, and B.T. Christensen (ed.) Managing Soil Quality: Challenges in modern agiculture. CABI Publishing, Oxon, United Kingdom.

Drinkwater, L.E., C.A. Cambardella, J.D. Reeder, and C.W. Rice. 1996. Potentially mineralizable nitrogen as an indicator of biologically active soil nitrogen. p. 203-229. *In* J.W. Doran, and A.J. Jones (ed.) Methods for assessing soil quality. SSSA Spec. Publ. 49. SSSA, Madison, WI.

Easton, E.F. 1976. Use of ammonium electrode for total nitrogen determination in plants. Comm. Soil Sci. Plant Anal. 3:477-481.

Elliot, E.T. 1986. Aggregate structureand carbon, nitrogen, and phosphorus in native and cultivated soils. Soil Sci. Soc. Am. J. 50:627-633.

Franzluebbers, A.J., R.L. Haney, C.W. Honeycutt, H.H. Schomberg, and F.M. Hons. 2000. Flush of carbon dioxide following rewetting of dried soil relates to active organic C pools. Soil Sci. Soc. Am. J. 64:613-623.

Gregorich, E.G., M.R. Carter, D.A. Angers, C.M. Monreal, and B.H. Ellert. 1994. Towards a minimum data set to assess soil organic matter quality in agricultural soils. Can. J. Soil Sci. 74:367-385.

Gregorich, E.G., M.R. Carter, J.W. Doran, C.E. Pankhurst. 1997. Biological attributes of soil quality. p.81-113. *In* E.G. Gregorich and M.R. Carter (ed.) Soil quality for crop production and ecosystem health. Elsevier Science Publishers B.V., Amsterdam, The Netherlands.

Gruver, J.B., and R.R. Weil. 1998. Simplified method for determination of aggregate stability for soil quality assessment, pp. 220 1998 Agronomy abstracts. ASA, Madison, WI.

Gruver, J.B. 1999. Relationships between farmer perceptions of soil quality and management sensitive soil parameters. M.S. Thesis. University of Maryland, Colllege Park, MD.

Hermawan, B., and A.A. Bomke. 1997. Effects of winter cover crops and successive spring tillage on soil aggregation. Soil Tillage Res. 44:109-120.

Hurlbert, S.H. 1984. Pesudoreplication and the design of ecological field experiments. Ecol. Monogr. 54:187-211.

Hu, S., N.J. Grunwald, A.H.C. van Bruggen, G.R. Gamble, L.E. Drinkwater, C Shennan, and M.W. Demment. 1997. Short-term effects of cover crop incorporation on soil carbon pools and nitrgen availability. Soil Sci. Soc. Am. J. 61:901-911.

Islam, K.R. and R.R. Weil. 2000. Soil quality indicator properties in mid-Atlantic soils as influenced by conservation management. J. Soil Water Conserv. 55:69-78.

Jenkinson, D.S. 1988a. Determination of microbial biomass carbon and nitrogen in soil. p. 368-386. *In* J.R. Wilson (ed.) Advances in nitrogen cycling in agricultural ecosystems. CABI Publishing, Oxon, England

Jenkinson, D.S. 1988b. Soil organic matter and its dynamics. p. 564-607. *In* A. Wild (ed.) Russell's soil conditions and plant growth. 11th ed. Longman, New York.

Karlen, D.L., N.S. Eash, and P.W.Unger. 1992. Soil and crop management effects on soil quality indicators. Am J. Altern. Agric. 7:48-55.

Kemper, W.D. and R.C. Rosenau. 1986. Aggregate stability and size distribution. p. 425-442. *In* Methods of soil analysis, Part 1. Physical and Mineralogical Methods—Agronomy Monograph no. 9. 2nd edition. Agronomy Society of America, Madison, WI.

Kennedy, A.C., and R.I. Papendick. 1995. Microbial characteristics of soil quality. J. Soil Water Conserv. 50:243-248.

Kortleven, J. 1963. Quantitative aspects of humus accumulation and decomposition. Versl. Landb. Ond. nr. 69.1 PUDOC, Wageningen (in Dutch).

Kuo, S., Sainju, U.M., and E.J. Jellum. 1997. Winter cover crop efects on soil organic carbon and carbohydrate in soil. Soil Sci. Soc. Am. J. 61:145-152.

Larson W.E., and F.J. Pierce. 1994. The dynamics of soil quality as a measure of sustainable management. p. 37-51. *In* J.W.Doran, D.C. Coleman, D.F. Bezdicek, and B.A. Stewart (ed.) Defining soil quality for a sustainable environment. SSSA Spec. Publ. 35. SSSA, Madison, WI.

Liebig, M.A. and J.W. Doran. 1999. Evaluation of farmers' perceptions of soil quality indicators. Am. J. Alt. Agric. 14:11-21.

Mendes, I.C., A.K. Bandick, R.P. Dick, and P.J. Bottomley. 1999. Microbial biomass and activities in soil aggregates affected by winter cover crops. Soil Sci. Soc. Am. J. 63:873-881.

Potter, K.N., H.A. Tolbert, O.R. Jones, J.E. Matocha, J.E. Morrison, and P.W. Unger. 1998. Distributionan amount of soil organic C in long-term management systems in Texas. Soil Tillage Res. 47:309-321.

Saviozzi, A., A. Biasci, R. Riffaldi, and R. Levi-Minzi. 1999. Long-term effects of farmyard manure and sewage sludge on some soil biochemical characteristics. Biol. Fertil. Soil. 30:100-106.

Seybold, C.A., M.J. Mausbach, D.L. Karlen, and H.H. Rogers. 1996. Quantification of soil quality. p.53-68. *In* T.S.Q. Intitute (ed.) The soil quality concept. USDA/NRCS, Washington, D.C.

Sikora, L.J., and D.E. Stott. 1996. Soil Organic Carbon and Nitrogen. p. 157-167. *In* J.W.Doran and A.J. Jones (ed.) Methods for assessing soil quality. SSSA Spec. Publ. 35. SSSA, Madison, WI.

Stine, M.A., and R.R. Weil. 2002. The relationship between soil quality and crop productivity across three tillagesystems in south central Honduras. Am. J. Altern. Agric. 17:2-8.

Tabatabai, M.A., and J.M. Bremner. 1991. Automated instruments for determination of total carbon, nitrogen, and sulfur in soils by combustion techniques. p. 261-286. *In* K.A. Smith (ed.) Soil analysis: Modern instrumental techniques. 2nd ed. Dekker, New York.

Topp, G.C., W.D. Reynolds, F.J. Cook, J.M. Kirby, and M.R. Carter. 1997. Physical attributes of soil quality. p. 21-58. *In* E.G. Gregorich and M.R. Carter (ed.) Soil quality for crop production and ecosystem health. Elsevier Science Publishers B.V., Amsterdam, The Netherlands.

Tisdall, J.M., and J.M. Oades. 1982. Organic matter and water stable aggregates in soils. J. Soil Sci. 33:141-163.

Wagger, M.G., M.L. Cabrera, and N.N. Ranells. 1998. Nitrogen and carbon cycling in relation to cover crop residue quality. J. Soil Water Conserv. 53:214-218.

Wander, M.M., S.J. Traina, B.R.Stinner, an S.E. Peters. 1994. Organic and conventional management effects on biologically active soil organic matter pools. Soil Sci. Soc. Am. J. 8:1130-1139.

Wander, M.M., and M.G. Bidart. 2000. Tillage practice influences on the physical protection, bioavailability and composition of particulate organic matter. Biol. Fertil. Soils 32:360-367.

Wander, M.M., and L.E. Drinkwater. 2000. Fostering soil stewardship through soil quality assessment. Appl. Soil Ecol. 15:61-73.

Weil, R.R., K.R. Islam, M.A. Stine, J.B. Gruver, and S.E. Samson-Liebig. 2003. Estimating active carbon for soil quality assessment: A simplified method for lab and field use. Am. J. Altern. Agric. 18:3-17.

Chapter Four

Bauer, P.J., and W.J. Busscher, 1996. Winter cover and tillage influences on Coastal Plain cotton production. J. Product. Agric. 9:50-54.

Biederbeck, V.O., H.H. Janzen, C.A. Campbell, R.P. Zentner. 1994. Labile soil organic matter as influenced by cropping practices in an arid environment. Soil Biol. Biochem. 26:1647-1656.

Blevins, R.L., J.H. Herbeck, and W.W. Frye. 1990. Legume cover crops as a nitrogen source for no-till corn and grain sorghum. Agron. J. 82:769-772.

Dabney, S.M., J.A. Delgado, and D.W. Reeves. 2001. Using winter cover crops to improve soil and water quality. Commun. Soil Sci. Plant Anal. 32:1221–1250.

Dick, W.A., and E.G. Gregorich. 2004. Developing and maintaining soil organic matter levels. p. 103-120. In P. Schjonning, S. Elmholt, and B.T. Christensen (ed.) Managing Soil Quality: Challenges in modern agiculture. CABI Publishing, Oxon, United Kingdom.

Eckert, D.J. 1988. Rye cover crops for no-tillage corn and soybean production. J. Prod. Agric. 1:207-210.

Gale, W.J. and C.A. Cambardella. 2000. Carbon dynamics of surface residue- and root-derived organic matter under simulated no-till. Soil Sci. Soc. Am. J. 64:190-195.

Gregorich, E.G., M.R. Carter, D.A. Angers, C.M. Monreal, and B.H. Ellert. 1994. Towards a minimum data set to assess soil organic matter quality in agricultural soils. Can. J. Soil Sci. 74:367-385.

Gruver, J.B. 1999. Relationships between farmer perceptions of soil quality and management sensitive soil parameters. M.S. Thesis. University of Maryland, Colllege Park, MD.

Hermawan, B., and A.A. Bomke. 1997. Effects of winter cover crops and successive spring tillage on soil aggregation. Soil Tillage Res. 44:109-120.

Hu, S., N.J. Grunwald, AH.C. van Bruggen, G.R. Gamble, L.E. Drinkwater, C Shennan, and M.W. Demment. 1997. Short-term effects of cover crop incorporation on soil carbon pools and nitrgen availability. Soil Sci. Soc. Am. J. 61:901-911.

Islam, K.R. and R.R. Weil. 2000. Soil quality indicator properties in mid-Atlantic soils as influenced by conservation management. J. Soil Water Conserv. 55:69-78.

Kabir, Z. and R.T. Koide. 2002. Effect of autumn and winter mycorerhizal cover crops on soil properties, nutrient uptake and yield of sweet corn in Pensylvania, USA. Plant Soil 238:205-215.

Kessavalou, A., and D.T. Walters. 1997. Winter rye as a cover crop following soybean under conservation tillage. Agron. J. 89:68-74.

Kuo, S., Sainju, U.M., and E.J. Jellum. 1997. Winter cover crop efects on soil organic carbon and carbohydrate in soil. Soil Sci. Soc. Am. J. 61:145-152.

Lal, R. 1997. Land use and soil management effects on soil organic matter dynamicson Alfisols in Western Nigeria. In: R Lal, J.M. Kimble, R.F. Follett, and B.A. Stewart. (eds.) Soil processes and the carbon cycle. CRC Press, Boca Raton, Fl.

Large, E.C. 1954. Growth stages in cereals. Illustration of the Feekes scale. Plant Pathol. 3:128-129.

Magdoff, F. 1996. Soil organic matter fractions and implications for interpreting soil organic matter tests. p. 11-19. In F.R. Magdoff, M.A. Tabatabai, and E.A. Hanlon, Jr. (ed.) Soil organic matter: Analysis and interpretation. SSSA Spec. Publ. 46. SSSA, Madison, WI.

McCracken, D.V., S.J. Corak, M.S. Smith, W.W. Frye, and R.L.Blevins. 1989. Residual effects of nitrogen fertilization and winter cover cropping on nitrogen availability. Soil Sci. Soc. Am. J. 53:1459-1464.

Mendes, I.C., A.K. Bandick, R.P. Dick, and P.J. Bottomley. 1999. Microbial biomass and activities in soil aggregates affected by winter cover crops. Soil Sci. Soc. Am. J. 63:873-881.

N'Dayegamiye, A., and T.S. Tran. 2001. Effects of green manures on soil organic matter and wheat yields and N nutrition. Can. J. Soil Sci. 81:371-382.

Ndiaye, E.L., Sandeno, J.M., McGrath, D. and R.P. Dick. 2000. Integrative biological indicators for detecting change in soil quality. Am. J. Alt. Agric. 15:26-36.

Odland, T.E., and H.C. Knoblauch. 1938. The value of cover crops in continuous corn culture. J. Am. Soc. Agron. 30:22-29.

Puget, P. and L.E. Drinkwater. 2001. Short-term dynamics of root and shoot derived carbon from a leguminous green manure. Soil Sci. Soc. Am. J. 65:771-779.

Raimbault, B.A., T.J. Vyn, and M. Tollenaar. 1990. Corn Response to rye cover crop management and spring tillage systems. Agron. J. 82:1088-1093.

Reeves, D. W. 1994. Cover crops and rotations. pp.125–172. In: J.L. Hatfield and B.A. Stewart (eds.) Crops Residue Management. Advances in Soil Science. Lewis Publishers, Boca Raton, FL.

Sainju, U.M., B.P. Singh, and W.F. Whitehead. 1998. Cover crop root distribution and its effects on soil nitrogen cycling. Agron. J. 90:511-518.

Sainju, U.M., B.P. Singh, and W.F. Whitehead. 2000. Cover crops and nitrogen fertilization effects on soil carbon and nitrogen and tomato yield. Can. J. Soil Sci. 80:523-532.

Sainju, U.M., B.P. Singh, and W.F. Whitehead. 2001. Comparison of the effects of cover crops and nitrogen fertilization on tomato yield, root growth and soil properties. Scientia Horticulturae 91:2001-214.

Smith, M.S., W.W. Frye, and J.J. Varco. 1987. Legume winter cover crops. Adv Soil Sci. 7:95-139.

Staver, K.W. and R.B. Brinsfield. 1998. Using cereal grain winter cover crops to reduce groundwater nitrate contamination in the mid-Atlantic coastal plains. J. Soil Water Cons. 53:230 –240.

Wagger, M.G., M.L. Cabrera, and N.N. Rannels. 1998. Nitrogen and carbon cycling in relation to cover crop residue quality. Soil Water Cons. 53:214-224.

Weil, R.R., and F. Magdoff. 2004. Significance of soil organic matter to soil quality and health. p. 1-43. In F. Magdoff and R.R. Weil (ed.) Soil organic matter in sustainable agriculture. CRC Press. Boca Raton, FL.