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Soil aggregate dynamics and aggregate-associated carbon under different vegetations types in riparian soils

Carmen Omaira Marquez

Iowa State University

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Soil aggregate dynamics and aggregate-associated carbon under different vegetation types in riparian soils

by

Carmen Omaira Marquez

A dissertation submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Forestry (Forest Biology – Wood Science)

Major Professor: Richard C. Schultz

Iowa State University

Ames, Iowa

2001
This is to certify that the Doctoral Dissertation of

Carmen Omaira Marquez

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Major Professor

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For the Major Program

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For the Graduate College
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ABSTRACT

Forest and grass riparian buffer systems provide year-round soil cover, limiting erosion, and favoring soil development processes by potentially increasing soil C sequestration. Plant-soil interactions influence patterns of soil aggregation and organic matter storage. And have a major positive impact on the soil ecological functions that maintain and enhance both water and environmental quality. In this dissertation a new theoretical and experimental framework is presented that introduces the concept and determination of aggregate size-stability distribution. In addition, two new indexes, the soil stability index and the total soil stability index, both based on aggregate, are proposed for studying soil stability. Finally, the soil aggregates dynamics model that integrates the aggregation, disruption, stabilization, and destabilization processes of soil aggregates, is developed for studying soil aggregate dynamics.

The size-stability distribution and the soil aggregate dynamics model were used to assess aggrading and degrading processes that occur in riparian soils. Pooled data from 1997 and 1998 showed that the major soil process following conversion of cool-season grass to agricultural row crops is disruption, with 19% of the large and small macroaggregates being disrupted. This disruption of macroaggregates exposes previously protected labile organic carbon to decomposers, resulting in a loss of 11.3 mg C g⁻¹ soil and further destabilizing the macroaggregates. The amount of total particulate organic C was three times greater under cool-season grass than under cropped system and accounted for 16% of the total organic carbon under and 7% under cropped system. The results indicate that macroaggregates under cool-season grass are more stable and provide an important mechanism for C sequestration supporting higher amounts of both light and heavy particulate organic matter than cropped
system. Additional results indicate that the "net" soil aggregate process in a 7-year old switchgrass stand that was converted from a cropped system is aggregation, which yields 3% new unstable macroaggregates. The storage of soil organic C under switchgrass occurs at a rate of $\sim 43 \text{ g m}^{-2} \text{ y}^{-1}$. The low rate of aggregation, soil stabilization, and soil organic C storage under switchgrass is related to: (i) the large number of coarse roots, (ii) lower inputs of light and heavy particulate organic matter, (iii) no change in the alkyl-C/O-alkyl-C ratio over time, and (iv) light Particulate organic matter-C with a high C/N ratio.
INTRODUCTION

Riparian zones have important geomorphic and hydrologic roles and support high levels of biological productivity (Van and Jackson, 1990). Although riparian areas may occupy only a small area of a watershed, they represent an extremely important component of the overall landscape (Elmore and Breschta, 1987). Healthy riparian areas stabilize stream channels, provide sediment storage, serve as nutrient sinks for the surrounding watershed, and improve the quality of water leaving the watershed (DeBano and Schmidt, 1989).

Agriculture in the Midwestern USA has removed most native ecosystems from the landscape. Most riparian zones have been negatively influenced by human activities. Thus, the loss of these ecosystems has increased the potential for non-point source pollution of surface and groundwater systems. Frequent disturbance events in riparian zones have consequences such as pollution of water, hydraulic alteration of waterways, reduction in soil quality, and disruption of wildlife habitats and populations. The riparian ecosystem of a stream especially critical to the processes of surface water quality protection (Schultz et al., 1995)

Soil degradation jeopardizes the soil's capacity to perform its functions of ecosystem productivity and to maintain environmental quality (Lal, 2000). Soil degradation is a severe global issue, and predominant degradative processes are accelerated erosion, depletion of soil organic matter and plant nutrients, and a decline in soil structure (Lal, 2000). Considerable attention has been focused on the restoration of riparian forest and grasses buffer systems to filter sediment, nutrients, and pesticides entering from upslope agricultural fields (Hubbard and Lowrance, 1996). Forests reduce erosion by improving water infiltration, intercepting rain and snow thereby reducing the impacts of water droplets, and by physically stabilizing
soil with their roots and leaf litter. Perennial grasses reduce water runoff, sediment loss, and help soil development processes by improving soil organic matter, soil structure, and soil water and nutrient-holding capacity (Kort et al., 1998).

Numerous approaches have been adopted for mitigating the adverse impacts of agriculture practices within the context of a bioassimilative strategy. These include the restoration of riparian vegetative buffer strips (Osborne and Kovacic, 1993). In 1990, the Agroecology Issue Team (AIT) of the Leopold Center for Sustainable Agriculture constructed a multi-species riparian buffer system along a central Iowa stream. Bear Creek is typical of many streams in central Iowa where the primary land use along the stream’s length is row crop (corn and soybean) agriculture or intensive riparian zone grazing (Schultz et al., 1995).

Most programs for managing non-point-source pollutants favor forest for riparian vegetation because of their documented ability to remove nitrate and retain sediment (Lowrance et al. 1984; Corre et al., 1999). In the northeastern USA, native cool-season grass (C3) has been used to revegetate stream banks (Corre et al., 1999).

In addition, warm-season grasses (C4) have been used to restored areas in Central Iowa because they have extensive root system, and dense, stiff stems, that provides frictional surface to intercept concentrated overland flow and convert it to sheet flow which leads to deposition sediment in the strip (Schultz, et al., 1995).

Five years after establishment of the multi-species riparian buffer Schultz, et al (1995), reports that there has been dramatic alteration in the appearance and functioning of this riparian zone. After four growing seasons, early root biomass estimates indicate significantly
more root biomass below the multi-species riparian buffer system than under agricultural fields.

**Plant Species Effects on Soil Properties**

In general, detectable changes in soil properties must be expected when one ecosystem is replaced by another (Milles, 1985; Singh, et al. 1985). Available research reports profound changes soil organic matter, pH, exchangeable base content, structure, horizon thickness, color, and boundary sharpness as of consequence in changes in vegetation (Lodhi, 1977). The most significant changes in soil parameters of the soil, related to vegetation, occur at or near the surface and are related to the supply of organic matter from leaf litter (Mergen and Malcom, 1995; Lundgren 1978; Rab, 1994; Marquez, et al., 1993).

Investigating soil properties under different types of forest vegetation showed that a pure mixed tree plantation, such as organic matter and structure more than pure species plantation (Singh, et al., 1985). Similar results were reported by (Challinor, 1967) who found improvement in aeration and porosity in the upper horizons of a forest soil as a result of afforestation. Lundgren (1978) indicated a trend toward an initial improvement in soil structure and decreased bulk density over the first 4 years in an agroforestry system.

The functioning of soil is profoundly influenced by its organic matter content. The ability of a soil to supply nutrients, store water, release greenhouse gases, modify pollutants, resist physical degradation, and produce crops within a sustainably managed framework are all strongly affected by the quality and quantity of the organic matter that it contains (Ress et al., 2000).
The organic matter content of a soil is profoundly influenced by the cropping system imposed on it (Janzen et al., 1992). Long-term cultivation alters soil structure and increases the losses of soil organic matter (Dalai and Mayer, 1986).

The importance of a continuous supply of C as an energy source for sustained NO$_3^-$ removal by denitrifying bacteria suggests that linkages between vegetation and denitrification are important in riparian zones (Hill, 1996). Osborne and Kovacic (1993) reported that a forest riparian zone in Illinois was more efficient at removing NO$_3^-$ from the riparian zone than an adjacent grass riparian area. However, Schanabel, et al (1996) found that a grasses riparian site exhibited greater denitrification rates than the wooded site, when denitrification rates were limited by organic C in the wooded riparian ecotone. Lowrance (1992) found that riparian sub-soils did not have sufficiently high levels of C to support significant active populations of denitrifiers. Riparian zones may affect denitrification by supplying C as an energy source to denitrifying bacteria through litter decomposition and root exudates (Haycock and Pinay, 1993; Hill, 1996).

In aggrading systems, plant species can differ in the ability to influence soil aggregation and improve soil productivity by carbon sequestration. Carbon is added to the soil mainly by deposition and decay of plant material on the surface and by root growth and senescence below the surface. The types of roots produced by different plants and their density and architecture can influence macroaggregate size distribution (Miller and Jastrow, 1990). However, in aggrading systems, plant species can differ in the ability to influence soil aggregation and improve soil productivity by carbon sequestration. For example, Jastrow (1987) concluded that an increase in root production and root biomass under C4 prairie graminoids may confer some advantage over introducing C3 Eurasian grasses for the
development of water stable aggregates. Switchgrass may improve soil quality by
sequestering C in the switchgrass-soil agroecosystem owing to its high biomass (Sladden, et
al., 1991) and deep rooting system (Ma et al., 2000). However, Scott (1998) reported that C4
grasses had no effect on aggregate-size distribution or organic matter concentration in spite
of two-fold differences in root biomass and a three-fold difference in N cycling. Similarly,
Corre et al., (1999) concluded that slow accumulation of C4-derived soil organic carbon is an
important consideration in its use in restoring riparian and conservation areas. Indeed
Franzluebbers et al (2000) reported that storage of soil organic carbon occurred at a rate of
$\sim 100 \text{ g m}^{-2} \text{ y}^{-1}$ during the first 10 years of establishment under grazed tall fescue (C3) and at
rate of $\sim 33 \text{ g m}^{-2} \text{ y}^{-1}$ under hayed bermudagrass (C4). In agreement with these results Ma, et
al (2000) concluded that several years of switchgrass culture would be required to realize a
soil C sequestration benefit. No increases in structural stability occurred during the 3 yr time
period corn treatments. In contrast, all the C3 grass treatments resulted in highly significant
rates of structural improvement (Perfect et al., 1990a).

Previous studies present conflicting conclusions on the effect of riparian vegetation on
the stream water quality, aggregates, and soil organic matter. The results apparently
depended on operational differences between studies and on actual differences between
systems. Previous investigations of effects of vegetation communities on soils is not clear
mainly due to (i) lack of replications (ii) soil types are different; iii) lack of complete
collection of data-soil texture, pH, bulk density and (iv) previous history of the landscape.

The technical aspect of assessing or monitoring effects of species on soil properties
involves some of the aspects proposed by (Carter, 2000) who defines a sequential framework
to evaluate soil quality for a specific purpose.
Table 1. Sequential framework to evaluate soil quality for a specific purpose or fitness of use (after Carter et al., 1997).

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<td>What will be the soil used by?</td>
</tr>
<tr>
<td>2</td>
<td>Functions</td>
<td>What specific role is being asked of the soil?</td>
</tr>
<tr>
<td>3</td>
<td>Processes</td>
<td>What key soil processes support each function?</td>
</tr>
<tr>
<td>4</td>
<td>Properties/attributes</td>
<td>What are the critical soil properties for each process?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>What are their critical or “threshold” values?</td>
</tr>
<tr>
<td>5</td>
<td>Indicators/surrogates/ pedotransfer functions</td>
<td>When the attribute is difficult to measure or not available, which indirect or related property can be used in its place?</td>
</tr>
<tr>
<td>6</td>
<td>Methodology standardization</td>
<td>What methods are available to measure the attributes?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Technical rules and protocols for soil sampling, handling, storage, analysis and interpretation of data.</td>
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The sequential framework given in Table 1 can be used to investigate the relationship between species characteristics and soil properties using two indicators such as soil stable aggregates and total soil organic carbon (Karlen et al, 1994). The relevance of these two indicators is that they are related with physical and biological functions that occur under riparian soils. Organic matter is both a source and a sink for plants nutrients, and provides an energy substrate for soil organisms (Carter, 2000). Soil macro-and microaggregation is promoted and stabilized by soil organic matter (Tisdall, 1996). The positive interrelationship between soil organic matter and soil aggregation has important benefits for both water and air infiltration, soil erodability, and conservation of organic matter and nutrients (Feller and Beare, 1996).

Knowledge about the processes and mechanisms influencing dynamics of soil aggregates, is important to completely understanding of the carbon cycle. In soils at or near equilibrium in terms of the amount of soil organic matter in the whole soil, which neither organic matter
nor aggregates are static, and the turnovers of aggregates and various organic matter pools are still interrelated; (i) in degrading systems, in which the disruption of aggregates exposes previously protected but relatively labile organic matter to decomposers, resulting in a loss of soil organic matter and further destabilization of aggregates; (ii) in aggrading systems, organic inputs lead to the formation and stabilization of aggregates, which in turn can protect soil organic matter from decomposition, leading to further aggregates stabilization (Jastrow and Miller, 1998). In any case, the feedbacks between soil organic matter cycling and aggregate cycling appear to be controlled by the formation and destruction of organomineral associations functioning as aggregate binding agents (Jastrow and Miller, 1998).

**Approaches to study soil organic matter**

Soil organic matter dynamics play a major role in natural ecosystems and intensive agriculture (Paul, 1984). The Soil Science Society of America (1987) defines soil organic matter as the organic fraction of soil exclusive of undecayed plant and animal residue. This definition, however, seems too restrictive given the fact that most analytic procedures for soil organic matter do not distinguish between decomposed and undecomposed plant and animal residues and living organisms in soils sieved to < 2 mm before analysis (Sikora et al., 1996; Sikora and Scott, 1996). In the broadest sense, soil organic matter pools encompass plant, animal, and microbial residues in all stages of decay and a diversity of heterogeneous organic substances intimately associated with inorganic soil components (Christensen, 1992). As a consequence, soil organic matter can be conceptually defined as a series of fractions that comprise a continuum based on decomposition rate (Christensen, 1996).
Turnover of soil organic matter represents energy and nutrient flows of a soil and therefore is closely related to intrinsic soil productivity (Hsieh, 1996). The soil C content is highly correlated with soil productivity, erodibility, water infiltration, energy source and the capacity of the soil to act as an environmental buffer by absorbing potential pollutants (Sikora et al., 1996; Sikora and Scott, 1996). However, some researches have concluded that some of these processes are related more directly with to the most labile forms of soil organic matter, and not with the total soil organic matter content. According to Hsieh (1992), it is critically important to differentiate between the labile and stable pools of soil organic matter, because they play very different roles in regulating C and nutrient flows in soil. Active, slow and stable organic C pools have different functional roles in soil organic matter dynamics and nutrient cycling. Each pool, therefore, may respond differently to various soil and crop management practices (Karlen and Cambardella, 1996).

During the past 20 years, ample evidence has accumulated to demonstrate that fractionation of soil according to particle size provides a significant tool in the study of soil organic matter distribution and dynamics (Tiessen and Stewart, 1983; Christensen, 1992 Janzen et al., 1998). Physical fractionation techniques are considered less destructive, and the results acquired from analyses of these soil fractions have been used with some success to elucidate soil organic matter dynamics (Truncker and Oades, 1980; Tiessen and Stewart, 1983; Cambardella and Elliott, 1993a; Cambardella and Elliott, 1993b; Christensen, 1996). Current research suggests that characteristics of particulate organic matter, an analytic fraction obtained by physical fractionation of soil, are consistent with theoretical characteristics of intermediate labile soil organic matter pools. Particulate organic matter is a size-defined fraction and consists of partially decomposed pieces of plant residue with a C/N
ratio of about 20 (Cambardella and Elliot, 1992). Developing a better understanding of the particulate organic matter and other identifiable soil organic matter fractions may provide tools for quantifying the effects of alternate soil and crop management practices on both C storage and soil quality (Karlen and Cambardella, 1996).

Knowledge about the size and turnover of the components constituting the labile forms of the organic fraction can be used in the interpretation of the role of soil organic matter in ecosystem functioning (Paul, 1984) and also to understand the role of the turnover rates of organic matter serving as binding agents for micro- and macroaggregates such as was defined by (Tisdall and Oades, 1982). They presented a conceptual model of soil aggregation that describes the hierarchical structure of soil aggregates. Tisdall and Oades (1982) suggest that macroaggregates are composed of smaller microaggregates bonded together by organic agents. The organic matter between microaggregates within macroaggregates is transient in nature, and seems to be composed of microbial products, roots, and fungal hyphae. Since macroaggregates are destroyed with cultivation, macroaggregate stability is highest under pasture.

Cambardella and Elliot (1992, 1993b) reported that particulate organic matter is involved in formation and stabilization of macroaggregates. Several studies have demonstrated greater concentrations of organic C in macroaggregates than in microaggregates (Tisdall and Oades, 1982; Cambardella and Elliott, 1993b). However, others have found higher concentration of organic C in microaggregates than in macroaggregates (Beare et al., 1994; Seech and Beauchamp, 188).

Labile forms of soil organic matter, such as particulate organic matter, show promise as a short-term or early warning indicator of long-term changes in soil quality (Cambardella and
Elliott, 1993a). Much of the soil organic matter binding of microaggregates into macroaggregates was lost through mineralization during cultivation of grassland soils (Elliot, 1986). Macroaggregation and physical protection of soil organic matter are more closely linked to the abundance and turnover of particulate organic matter than total soil carbon levels (Cambardella and Elliott, 1993b).

Two important functions of organic matter must be understood to improve soil management in riparian zones. They are: (i) organic C availability and supply is an important linkage between vegetation and denitrification in riparian zones and (ii) the dynamics of carbon as the major binding agent in which microaggregates are bound together into macroaggregates plays an important role in soil porosity which influences infiltration and soil water storage and movement. All of these processes are related directly with infiltration, permeability, and also enhance the environmental conditions for denitrification.

Although difficulties still remain in defining sustainability (Ress et al., 2000) there is a consensus, that organic matter has significant role in the sustainability of an ecosystem (Switt and Woomer, 1993). But, because soil aggregation and soil organic matter are intimately associated with each other (Jastrow, 1987). The understanding of soil aggregation, stabilization and destabilization, in addition to carbon associated to these aggregates fractions in necessary to evaluate soil dynamics of aggregate and carbon associated with aggregates in aggrading, degrading and steady state systems. These studies are important to develop indices that can be used to determine present soil health, and assess degrees of soil deterioration, and predict threshold conditions before a soil or ecosystem “goes over the brink” of ecological deterioration (Miller, 1998).
Approaches to Characterize Water Stable Aggregates

Soil structure has a major influence on soil ability to support root-development, to receive, store, and transmit water, to cycle carbon and nutrients, and to resist soil erosion and the dispersal of chemicals of anthropogenic origin (Kay, 1998). Soil aggregate stability is the result of complex interactions among biological, chemical, and physical processes in the soil (Tisdall and Oades, 1982). Factors affecting aggregate stability can be grouped as abiotic (clay minerals, sesquioxides, exchangeable cations), biotic (soil organic matter, activities of plant roots, soil fauna, and microorganisms), and environmental (soil temperature and moisture) (Chen et al., 1998). The concept of aggregate stability depends on both the forces that bind particles together and the nature and magnitude of the disruptive stress (Beare and Bruce, 1993).

Several methods have been proposed to determine aggregate size distribution and stability of soil aggregates (Kemper and Rosenau, 1986). The suitability of these methods depends on the purpose of the study. The most widely used approaches are based on the *Wet-sieving method* (Kemper and Rosenau, 1986; Kemper, 1966). In this method, cyclically submerging and sieving soil into water emulates stresses involved in the entry of water into the soil aggregates. The moisture content of the soil aggregates prior to wet sieving controls the severity of the disruption (Kemper and Rosenau, 1986). Several studies have used capillary-wetted and slaked pretreatment (Elliot, 1986; Cambardella and Elliott, 1993a; Six et al. 1998) as a means to study soil aggregates. The *capillary-wetted pretreatment* involves slowly wetting the soil aggregates prior to wet sieving. This pretreatment produces minimal disruption, because misted aggregates do not buildup air pressure in pores and the air escapes with minimal aggregate disruption. In contrast, *slaked pretreatment* causes considerable
disruption, when air-dry soil is submerged in water; the air that is trapped inside soil pores is rapidly displaced with water as a consequence of the sudden release of this large buildup of internal air pressure, which disrupt weak aggregates (Cambardella and Elliott, 1993a; Gale et al., 2000).

The combined use of the capillary-wetted and the slaked pretreatments has shown to be suitable as a means for contrasting differences in aggregate size distributions for soils with different management histories and also understanding the factors that influence aggregate stability (Elliot, 1986; Cambardella and Elliott, 1993a; Six, et al. 1998). More recently Gale, et al (2000) used the comparison of slaked versus capillary-wetted pretreatments as a means to differentiate stable macroaggregates from unstable macroaggregates based on their resistance to slaking. Although the conceptualization of Gale's idea represents an important contribution, more work is needed to clearly separate the stable macroaggregates from the unstable macroaggregates and accurately specify aggregate size-stability distributions. The aggregate size-stability distribution is defined, as “a description of stable and unstable soil aggregates categorized by size and stability”

We hypothesize that using a subsequent slaking in addition to the slaking and capillary-wetted pretreatments should yield a more accurate determination of the amount of stable and unstable macroaggregates. This in turn can be used to determine the aggregate size-stability distribution. This information will improve our understanding of the dynamics of organomineral associations and soil quality and will contribute to the development indices for improving soil management. This conceptual framework eliminates misinterpretation induced by traditional approaches and is a valuable tool for monitoring soil aggregates
dynamics and carbon associated with aggregates, which play an important role in maintaining ecosystem sustainability.

**Approaches to study Soil Aggregate Dynamics**

Although many studies have examined the effects of soil aggregates on soil tilth, water relations, root penetration and erosion potential only a few have examined the role of aggregates in controlling soil ecosystem (Elliot and Coleman, 1988; Jastrow et al., 1998). Knowledge of the processes and quality is needed for developing appropriate indices and management systems that enhance soil capacity as a carbon sink (Lal, 2000). Stabilization and destabilization of soil aggregates involves a variety of physical, chemical, faunal and microbial processes. In soils where structural stability is controlled by organic carbon, a link exists between organic carbon decomposition and soil aggregate dynamics (Golchin et al., 1998). Stabilization of soil aggregates and organic matter are intimately associated with each other. In aggrading systems organic inputs lead to the formation and stabilization of aggregates, which in turn can protect soil organic carbon from decomposition, leading to further aggregate stabilization. In soils at or near steady state, in terms of the amount of soil organic carbon in the whole soil, neither organic carbon nor aggregates are static, and the turnover of aggregates and various organic carbon pools are interrelated (Jastrow and Miller, 1998). On the other hand, destabilization is connected with a series of field process such as decomposition of organic binding agents, water content, slaking, growing cycles, intensive agriculture and deforestation. In degrading systems, the disruption of aggregates exposes previously protected but relatively labile organic carbon to decomposers, resulting in a loss of SOC and further destabilization of aggregates (Jastrow and Miller, 1998).
The size-stability distribution of soil aggregates at any given time is the result of a myriad of biological, physical, and chemical processes that change the soil structure at different scales and at different rates. It is widely accepted that the processes affecting soil aggregate dynamics occur relatively quickly and continuously under laboratory and field conditions (Kay, 1990; Terpstra, 1989). Several models of aggregation divide soil into macroaggregates (>250μm) and microaggregates (<250μm) (Tisdall and Oades, 1989). A conceptual approach that can be used to describe the concept of aggregate hierarchy was described by Hadas (1987) and Dexter (1988) and further developed by Oades and Waters (1991) and Oades (1993). A number of researches have presented an alternative view of aggregation in which microaggregates are formed within existing macroaggregates (Oades 1984; Elliot and Coleman, 1988). Similarly a conceptual model to explain these mechanics was developed by Golchin et al., (1998) which assume that as particulate organic matter enters the soil from root or plant debris it becomes colonized by soil microbes and at the same time adsorbs mineral materials. This particulate organic matter is encrusted by mineral particles and becomes the organic cores of stable microaggregates and is protected for rapid decomposition. Traditional approaches to studying soil aggregate dynamics include: (i) methods that compare aggregation and aggregate stability among soil types sometimes varying in texture or management history, and (ii) methods that explicitly incorporate time for studies of aggregation over long period of time (Kay, 1998; Perfect et al. 1990b). Methods that compare aggregation and aggregate stability among soil types are normally restricted to a small number of soil types and do not explicitly include time as an independent variable. These methods are basically a qualitative analysis of the shape and changes of aggregate size distribution (Christensen, 1992). Methods that explicitly incorporate time into
studies of aggregation are based on a conceptual model proposed by Kay et al., (1988) in which; 

(i) changes in relative aggregate stability compared to a reference state are a function of changes in the concentration of stabilizing materials relative to their amount in the reference state and 

(ii) the changes in stabilizing materials are a function of time. Perfect et al., (1990a) used this conceptual model to study temporal changes in water aggregate stability (WAS) (Perfect et al., 1990a). Perfect et al., (1990b) found that the empirical regression equation that best described their data was of the form: 

\[ WAS = WAS_{\text{max}} - Me^{bt} \]

where \(WAS\) and \(WAS_{\text{max}}\) are the measured and maximum water aggregate stabilities, respectively, \(M\) is a constant that is a function of the water content; \(M = WAS_{\text{max}} - WAS_{t=0}\), \(b\) is the rate constant with typical values between 0.08 and 0.30 per year, and \(t\) is time in years. This relationship provides the opportunity to analyze soil aggregate stability over long periods of time and is suitable for comparisons over a wide range of soils under different vegetation.

At present, there are no models and or analytical tools that integrate the aggregation, disruption, stabilization and destabilization processes in a framework that could make it easy to study soil aggregates dynamics and total carbon associated with aggregates over time or in comparing aggrading, degrading or steady-state ecosystems. In order to correctly understand the complex dynamics of soil aggregation and stabilization, it is necessary to integrate all of the processes involved in soil aggregate dynamics and its relationship with organic mater. Consequently, such information can lead to improved approaches to soil monitoring, management and minimize deterioration of the environment.
Knowledge Gaps

i) Existing approaches for studying soil aggregates do not fully distinguish between stable and unstable aggregates based on their resistance to slaking. In turn, soil stability has been assessed by the wet-sieve method, which often gives unsatisfactory, or even misleading results.

ii) At present, there are no models and or analytical tools that integrate the aggregation, disruption, stabilization and destabilization processes in a framework that could make it uncomplicated to study soil aggregates dynamics and total carbon associated with aggregates over time or in comparing aggrading, degrading or steady-state ecosystems. Knowledge about the processes and dynamics of soil structure, and relationship between soil structure and soil quality for developing appropriate indices and management systems that enhance soil capacity as a C sink are needed (Lal et al., 1998).

iii) Relationship between species characteristics, soil aggregation, and carbon associated with aggregates is no clear and consistent.

Issues Addressed

i) A new theoretical and experimental framework that permits an accurate determination of aggregate size-stability distribution, which in addition to estimating aggregate size distribution distinguishes between amounts of stable and unstable macroaggregates. This conceptual framework eliminates misinterpretation induced by traditional approaches and provides a valuable tool for studying soil aggregates and to characterize the distribution of organic matter associated with an aggregate size distribution is presented.


**ii)** Two new indexes for studying soil stability based on aggregate SSD, the total soil stability index (TSSI) and the soil stability index (SSI) are proposed.

**iii)** A conceptual model of soil aggregate dynamics (SAD) that integrates the aggregation, disruption, stabilization and destabilization processes of soil aggregates in a framework that permits studying soil aggregate dynamics over time or comparing ecosystems such as aggrading, degrading or steady-state systems is proposed.

**iv)** Using the aggregate size-stability index and the soil aggregate dynamics model we were able to assess and monitor aggrading and degrading process that occur under riparian soils.

**Objectives**

This dissertation address aggregate dynamics and carbon associated with aggregates from different vegetation types in riparian zones. The specific objectives of the study were:

1. **Develop a method for determining aggregate size-stability distribution; to develop a simple index for soil stability based on aggregate size stability distribution, and to test the suitability of the new method for quantifying soil stability and the new indexes by detecting differences in soil aggregate stability under different riparian plant communities.**

2. **Develop a conceptual model to study soil aggregates dynamics and this model integrates the aggregation, disruption, stabilization and destabilization processes of soil aggregate.**

3. **Assessing soil degradation after conversion of long established riparian cool-season grass filter to agricultural production.**
4. Assessing soil aggradation after conversion of agricultural production to switchgrass buffer filter.

5. Evaluation of the relative contribution of using organic matter fractions as an indicator of assessing soil quality in a riparian buffer system.

Dissertation Organization

The dissertation is organized into six chapters. The first chapter is a general introduction, which is divided into two sections: literature review and dissertation organization. The second chapter is a research manuscript that presents a new theoretical and experimental framework that permits an accurate determination of aggregate size-stability distribution, which in addition to estimating aggregate size distribution distinguishes between amounts of stable and unstable macroaggregates. The third chapter is a research manuscript in which present a conceptual model of soil aggregate dynamics that integrates the aggregation, disruption, stabilization and destabilization processes of soil aggregates in a framework that permits studying soil aggregate dynamics over time or comparing ecosystems such as aggrading, degrading or steady-state systems. The fourth chapter contains manuscript that assesses soil degradation under cropped system. The fifth chapter is manuscripts that assess soil-aggrading process after conversion of agricultural production to switchgrass buffer filter. These four manuscripts are prepared for publication in the Soil Science Society of America Journal. The sixth chapter is manuscript that examines the relative contribution of using organic matter fractions as an indicator of assessing soil quality in a riparian buffer system. This manuscript was been published in Agroforestry Systems. Finally, the seventh chapter contains a general conclusions section with some recommendations for future research.
References


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INTRODUCTION

Soil structure has a major influence on the ability of soil to support root-development, to receive, store, and transmit water, to cycle carbon and nutrients, and to resist soil erosion and the dispersal of chemicals of anthropogenic origin (Kay, 1998). Soil aggregate stability is the result of complex interactions among biological, chemical and physical processes in the soil (Tisdall and Oades, 1982). Factors affecting aggregate stability can be grouped as abiotic (clay minerals, sesquioxides, exchangeable cations), biotic (soil organic matter, activities of plant roots, soil fauna, and microorganisms), and environmental (soil temperature and moisture) (Chen et al., 1998). The concept of aggregate stability depends on both the forces that bind particles together and the nature and magnitude of the disruptive stress (Beare and Bruce, 1993).

Several methods have been proposed to determine soil aggregate size distribution and stability (Kemper and Rosenau, 1986). The suitability of these methods depends on the purpose of the study. The most widely used approaches are based on the Wet-sieving method (Kemper, 1966; Kemper and Rosenau, 1986). In this method, cyclically submerging and sieving soil in water emulates the natural stresses involved in the entry of water into soil aggregates. The moisture content of the soil aggregates prior to wet sieving controls the severity of the disruption (Kemper and Rosenau, 1986). Several studies have used capillary-wetted and slaked pretreatments (Elliot, 1986; Cambardella and Elliott, 1993a; Six, et al. 1998) as a means to study soil aggregates. The capillary-wetted pretreatment involves slowly wetting the soil aggregates prior to wet sieving. This pretreatment produces minimal disruption, because misted aggregates do not buildup air pressure in the pores and the air
escapes with minimal aggregate disruption. In contrast, the *slaked pretreatment* causes considerable disruption. When air-dry soil is submerged in water; the air that is trapped inside the soil pores is rapidly displaced with water. Weak aggregates are disrupted as a consequence of the sudden release of this large buildup of internal air pressure (Cambardella and Elliott, 1993a; Gale et al., 2000).

The combined use of the capillary-wetted and the slaked pretreatments has shown to be suitable as a means for contrasting differences in aggregate size distributions for soils with different management histories and also for understanding the factors that influence aggregate stability (Elliot, 1986; Cambardella and Elliott, 1993a; Six, et al., 1998). More recently, Gale et al. (2000) used the comparison of slaked versus capillary-wetted pretreatments as a means to differentiate stable macroaggregates from unstable macroaggregates based on their resistance to slaking. Although the conceptualization of Gale’s idea represents an important contribution, more work is needed to clearly separate the stable macroaggregates from the unstable macroaggregates and accurately specify aggregate size-stability distributions. The aggregate size-stability distribution is the quantity of stable and unstable soil aggregates categorized by their size and stability to disruption.

Existing approaches for studying soil aggregates do not fully distinguish between stable and unstable aggregates based on their resistance to slaking. In turn, this causes significant errors in assessing soil stability by the wet-sieve method and studying the dynamics of soil aggregates. The disruption of unstable macroaggregates during the slaking treatment produces smaller constituent aggregates that will be accounted for in smaller aggregate size fractions biasing the aggregate size-distribution. In contrast the capillary-wetted pretreatment
does not account for differences in stable and unstable macroaggregates because of the lack of violent disruption.

We hypothesize that using a subsequent slaking in addition to the slaking and capillary-wetted pretreatments should yield a more accurate determination of the amount of stable and unstable macroaggregates. This in turn can be used to determine the aggregate size-stability distribution. This information will improve our understanding of the dynamics of organomineral associations and soil quality and will contribute to develop indices for improving soil management. The objectives of this study are: (i) to develop a method for determining aggregate size-stability distribution, (ii) to develop a simple index for soil stability based on aggregate size-stability distribution, and (iii) to test the suitability of the new method for quantifying soil stability and the new indexes by detecting differences in soil aggregate stability under different riparian plant communities.

MATERIALS AND METHODS

Soil sampling

Surface soils from four different riparian plant communities under a cool season grass filter, an existing riparian forest, a 7-year switchgrass buffer, and from non-buffered annual row cropped areas in Central Iowa were sampled to a depth of 15 cm in September 1997. Three sample plots on similar, moderately drained, soils were collected from each of the four riparian plant communities. Table 1 shows a summary of the main characteristics of the soils in each of the treatments sites.
Aggregate separations

The field-moist soil was pushed through an 8-mm diameter sieve and air-dried. Two 100g subsamples of air-dried soil were used to analyze the aggregate size-stability distribution. One subsample was capillary-wetted to 5% soil moisture above field capacity and the other was left air-dry. The water pretreatments will be referred to as capillary-wetted (pre-wetted soil) and slaked (air-dry soil). Both subsamples were stored overnight in a refrigerator at 4 °C before wet sieving.

Subsamples were wet sieved following the protocol reported by Cambardella and Elliot (1993a). Aggregates were physically separated in four aggregate size fractions: (1) large macroaggregates greater than 2000 μm in diameter, (2) small macroaggregates between 250-2000 μm in diameter, (3) microaggregates between 53-250 μm in diameter, and (4) mineral fraction less than 53 μm in diameter. After wet sieving all the fractions were oven-dried at 70 °C, except the large and small macroaggregates obtained by the capillary-wetted pretreatment. These macroaggregates were air dried and later used for the separation of large and small stable macroaggregates. Sand corrections were performed after determination of the amount of sand in each size fraction (see appendix). The amount of sand was determined by sieving following dispersal of the aggregates with sodium hexametaphosphate (5g L⁻¹).

Determination of the aggregate size-stability distribution

The experimental procedure used to determine the aggregate size-stability distribution is shown in Figure 1. This procedure involves the slaked and capillary-wetted pretreatments; and a subsequent slaking treatment of aggregates in fraction one and two of the capillary-
wetted pretreatment. Theoretical considerations needed for the determination of the aggregate size-stability distribution are given below.

The determination of aggregate size-stability distribution involves the assumptions that soil aggregates can be categorized in terms of their size and water stability. Therefore:

1. Soil aggregates with diameters greater than 250 μm are labeled macroaggregates.

2. Macroaggregates are categorized as large-macroaggregates when their diameters are greater than 2000 μm (fraction 1) and small-macroaggregates when their diameters range between 250-2000 μm (fraction 2).

3. Macroaggregates are also categorized in terms of their resistance to slaking. Macroaggregates that survive slaking are labeled as stable and those that do not survive are labeled as unstable.

4. Microaggregates have diameters ranging between 53-250 μm (fraction 3).

5. The mineral fraction (silt + clay) has diameters less than 53 μm (fraction 4).

**Slaked pretreatment variables definition**

Variables and aggregate pathways during the slaking pretreatment are represented symbolically in Figure 2.

1. The total amount of aggregates collected in fraction one are labeled as \( T_{1S} \) and are stable large macroaggregates \( (S_1) \); \( T_{1S} = S_1 \).

2. The total amount of aggregates collected in fraction two are labeled as \( T_{2S} \), and are the small macroaggregates that survive slaking but with two different origins, the stable small macroaggregates that were in fraction two before slaking \( (S_2) \) and the stable small
macroaggregates that resulted from the fragmentation of unstable large macroaggregates upon slaking \((G_2)\); \(T_{25} = S_2 + G_2\).

3. The total amount of aggregates collected in fraction three are labeled as \(T_{35}\) and they are microaggregates with two different origins; microaggregates that were in fraction three before slaking \((S_3)\) and microaggregates that resulted from the disruption of unstable macroaggregates upon slaking in either fractions 1 and/or 2, are labeled \((G_3)\); \(T_{35} = S_3 + G_3\).

4. Finally, the material collected in fraction four is the mineral fraction \((T_{45})\), with two different origins; mineral-fraction that was in fraction four before slaking \((S_4)\) and mineral-fraction that resulted from the fragmentation of unstable macroaggregates upon slaking from all previous fractions, are labeled \((G_4)\); \(T_{45} = S_4 + G_4\).

The summation of the amount of aggregates collected in each size fraction after slaking should be equal to the total amount of soil \((T)\) used for this study; \(T = T_{15} + T_{25} + T_{35} + T_{45}\).

**Capillary- wetted pretreatment variables definition**

Variables and aggregates pathways involving during the capillary-wetted pretreatment are represented symbolically in Figure 3.

1. The total amount of aggregates collected in fraction one will be labeled as \(T_{icw}\) and are the stable large macroaggregates \((S_i)\) and the unstable large macroaggregates \((U_i)\); \(T_{icw} = S_i + U_i\).
2. The total amount of aggregates collected in fraction two are labeled as \( T_{2CW} \) and are the stable small macroaggregates \( (S_2) \) and the unstable small macroaggregates in this fraction \( (U_2) \); 
\[
T_{2CW} = S_2 + U_2.
\]

3. The aggregates collected in fraction three are labeled as \( T_{3CW} \) and are the microaggregates that could be found in this fraction before major perturbation of fractions one and two; 
\[
T_{3CW} = S_3.
\]

4. The mineral fraction collected in fraction four is labeled as \( T_{4CW} \) and is the mineral fraction that could be found before major perturbation of fractions one and two; 
\[
T_{4CW} = S_4.
\]

5. The total summation of the amount collected in each size class after the capillary-wetted pretreatment should be equal to the whole amount of soil \( (T) \) used for this study; 
\[
T = T_{1CW} + T_{2CW} + T_{3CW} + T_{4CW}.
\]

In addition to the slaked and capillary-wetted pretreatment we physically separated the amount of stable macroaggregates in fraction one and two from unstable macroaggregates by performing a second slaking treatment (Figure 1). We will refer this second slaking treatment as "subsequent-slaked" to differentiate this treatment from the slaked treatment (air-dry soil) initially performed to one set of the subsamples and to emphasize that it is after capillary-wetting, wet-sieving, and drying that this second slaking is performed. The subsequent-slaked treatment was performed based on the protocol suggested by the USDA (the slake test) to assess stability of the soil when exposed to rapid wetting (USDA, 1998;
Herrick, 1998). In addition to follow the USDA protocol we weighed the amount of aggregates that remained in the sieve after the subsequent slaking. The expected outcome from the subsequent slaked treatment is represented symbolically in Figure 3.

**Statistical Analyses**

Data were analyzed as a completely randomized block design using the SAS statistical package for analysis of variance (ANOVA-GLM, SAS Institute, 1990). Separation of means was tested using Contrast test significant difference with a 0.05 significance level.

**RESULTS AND DISCUSSION**

**Determination of stable and unstable macroaggregates**

The quantity of unstable large macroaggregates, can be calculated by subtracting the amount of stable large macroaggregates produced by the slaking treatment from the total amount of large macroaggregates produced by the capillary-wetted treatment;

\[ U_1 = T_{1cw} - T_{1s} \]

Because of the disruption of unstable large-macroaggregates upon slaking, this subtraction cannot be used for size class two. The subtraction of the slaking result from the capillary-wetted result in fraction two renders a value that is associated with the difference between the amount of unstable small macroaggregates and the amount of stable small macroaggregates that are gained in size fraction two, see equation [1]. Recall that \( T_{2cw} \) and \( T_{2s} \) were defined above and they are rewritten in equation [2] and [3].

\[ |T_{2cw} - T_{2s}| = |U_2 - G_1| \]  

[1]
The determination of $S_2$ and $U_2$ is not straightforward. The lack of information impairs the explicit calculation of the amounts of stable small macroaggregates and the amount of unstable small macroaggregates. There are three unknowns $S_2$, $U_2$, and $G_2$ and only two equations, equations [2] and [3]. The dilemma of the unknowns $S_2$, $U_2$, and $G_2$ could be overcome if we could determine the value of any of the three unknowns. One potential candidate is $S_2$, which could be estimated by performing a subsequent-slaking of the aggregates collected in fraction two after the initial capillary-wetted pretreatment. We will label the result of the subsequent-slaking as $T_{2SS}$ to differentiate this from the result of the slaking treatment ($T_{2S}$). The result of this subsequent slaking should be only stable small macroaggregates with $T_{2SS} = S_2$, (see Table 2). Upon the determination of $S_2$ we can use equations [2] and [3] to calculate $U2$ and $G2$.

One key point in the determination of $S_2$ using the subsequent-slaking treatment is the implicit hypothesis that the amount of stable and unstable aggregates does not change after the physical separation using the capillary-wetted treatment and air-drying the aggregates overnight. This hypothesis is supported by Kemper and Rosenau (1984) who studied soil cohesion as affected by time and water content. They found that the rate of change in cohesion is slower in air-dry soils and the mechanism of strengthening/weakening the bonding between particles is either lengthy cementing and diffusive processes or lengthy
dispersion processes. As a result, we do not expect major changes in the amount of stable and unstable aggregates after the capillary-wetted pretreatment. Experimentally we tested this hypothesis by performing a subsequent-slaking on 30 representative samples of macroaggregates collected in fraction one following the capillary-wetted pretreatment. We found that the amount of large macroaggregates that survive the subsequent-slaking \( T_{1ss} \) was highly correlated \( (r^2 = 0.96) \) with the amount of large macroaggregates that survived the slaking pretreatment, \( T_{1s} \) for the four field sites (Figure 4). In summary, the determination of the amount of stable and unstable aggregates involves the use of three treatments as is outlined in Figure 1 and the set of equations summarized in Table 2.

**Method Evaluation**

To test the method for determining the aggregate size-stability distribution we evaluated four different field sites with different types of vegetation. Table 3 presents results after using the approach outlined above. The distribution of soil aggregates among the different size fractions were significantly influenced by the vegetation type. The amount of large macroaggregates (> 2000μm) followed the order; cool-season grass > existing riparian forest > switchgrass = cropped system. The results in Table 4 indicate that 17% of the soil dry weight was present as stable large macroaggregates under cool-season grass, 10% under existing riparian forest, 3% under switchgrass, and 2% under cropped system.

In addition, cool-season grass showed significant differences in the distribution of small macroaggregates (250-2000μm) compared with the other vegetation types. There were no significant differences in the distribution of microaggregates (53-250μm) under the
vegetation types. The amount of unstable macroaggregates (>250μm) followed the order; cropped system > switchgrass = existing riparian forest > cool-season grass. These results indicate that 28% of the soil dry weight was present as unstable macroaggregates under cropped system, 23% under 7-year switchgrass, 19% under existing riparian forest, and 12% cool-season grass. These results support the hypothesis that cropping systems, that include the production of species with extensive root systems such as cool-season grass (C3 grasses), would produce the highest levels of macroaggregation. Haynes (1993) showed results that demonstrate the positive effect that a short term (5yr) pasture (C3 grasses) can provide more soil organic matter quantity and increased aggregate stability. Studies conducted by Tufekcioglu et al., (1999) in the same research area reported that cool-season grass had significantly greater dead fine root biomass than any of the other vegetation types. In addition, Pickle (1999) found that soil under cool-season grass had the highest amount of microbial biomass, followed by 7-year switchgrass and cropped system soil supported the lowest amount of microbial biomass. More large and stable macroaggregates were found under cool-season grass because the very fine dead roots and the high levels of microbial biomass provided a readily available source of labile C. The reduction of large and small macroaggregates in soils under cropped system has been clearly documented by this work. Long term cropping decreased the length and mass of fine roots, and soil organic matter resulting in a reduction of macroaggregates (Tisdall and Oades, 1980b, Cambardella and Elliot, 1992).
Index for Soil Stability

We mentioned in the introduction that soil aggregate stability is a major factor for assessing soil quality. Table 4 shows some of the indexes that have been proposed for quantitatively assessing soil stability. One common feature in these indexes is the lack of a clear differentiation in the amount of stable and unstable macroaggregates. More recent indexes are based on the subtraction of the mean value in the capillary-wetted pretreatment from the corresponding mean in the slaked pretreatment. Positive values are interpreted as a loss of material from the same fraction upon slaking. Negative values are interpreted as gains of material upon slaking. We have shown that misleading results emerge from using the difference between the values corresponding to fraction two.

The persistent search for a suitable index has evolved from simple metrics such as the mean weight diameter and water stable aggregates to more complex and elaborate metrics such as the aggregation index and the normalized stability index (van Bavel, 1949; Kemper, 1966; USDA, 1998; van Steenbergen, et al., 1991; Six et al., 2000) (Table 4).

The aggregate size-stability distribution may be used to assess soil stability. The rationale is that the amount of stable aggregates can be used as a metric for quantification and assessment of soil stability. We define the total soil stability index as the ratio between the total weighted average of stable aggregates before any perturbation of the soil and the total weighted average of soil aggregates including stable and unstable aggregates, equation [4].

\[
TSSI = \frac{\sum_{j=1}^{n} [(n+1) - j] S_j}{\sum_{j=1}^{n} [(n+1) - j] T_j}
\]
$S_j$ is the amount of stable aggregates in fraction $j$. $T_j$ is the total amount of aggregates in fraction $j$ (from the capillary-wetted treatment) and $n$ is the total number of size fractions.

We also define the soil stability index as the ratio between the weighted average of the amount of stable macroaggregates (> 250 $\mu$m) and the total weighted average of all soil aggregates, equation [5].

$$SSI = \frac{n \sum_{j=1}^{m} [(m+1) - j] S_j}{m \sum_{j=1}^{n} [(n+1) - j] T_j}$$

In these equations $m$ is the total number of size classes larger than 250 $\mu$m.

Equation [5] can be thought of as equivalent to the definition of the water stable aggregates, Kemper (1966), and USDA (1998). The difference is that the determination of the water stable aggregates involves either the slaked pretreatment or the capillary-wetted pretreatment and we have shown that the amount of stable small macroaggregates is overestimated by $G_2$ when using only slaked pretreatment. We also have shown that one or two pretreatments are not enough to determine the aggregate size stability distribution. Three treatments are needed to get an accurate assessment of both stable and unstable aggregate distribution, and thus a strong measure of soil stability. We also have shown that the slaked pretreatment produces an artificial redistribution of the unstable macroaggregates constituents that later are accounted for in the smaller fractions. We also have shown that the
capillary-wetted pretreatment gives only partial information about the distribution of the stable aggregates.

Table 5 compares the values for the indexes defined in equation [4] and [5] with other published indexes for soils under four types of vegetation. The total soil stability index and the soil stability index show a clear trend across the four vegetation types. Both the total soil stability and soil stability indices differed in the order cool-season grass > existing riparian forest > 7-year switchgrass = cropped system. The similarity in aggregation between 7-year switchgrass and cropped system is the result of the young age of the experiment (7 yr) and the type of native warm-season grass (C4 grass) that was used to restore the area that was cropped for many years.

Although the values for total soil stability and soil stability indices are significantly different for cool-season and existing riparian forest, the values of water stable aggregates using the capillary wetted pretreatment are not different. This is because the amount of aggregates (> 250 μm) that survive slaking for cool-season grass and existing riparian forest are not significantly different; $S_{15} + S_{25}$ is equal to 36.4 and 31.0 (Table 3) for cool-season grass and existing riparian forest, respectively. While the amount of stable macroaggregates given by the aggregate size-stability distribution is significantly different; $S_1 + S_2$ is equal to 31.4 and 19.4 for cool-season grass and existing riparian forest, respectively. The key point is that the lack of differentiation of stable and unstable macroaggregates is biasing the values of water stable aggregates using the slaked pretreatment.

The values of total soil stability and soil stability indices, and water stable aggregates using the slaked pretreatment are not significantly different for 7-year switchgrass and
cropped system. This is because the amounts of stable macroaggregates given by the aggregate size-stability distribution are not significantly different; \( S_1 + S_2 \) is equal to 13.8 and 13.1 for 7-year switchgrass and cropped system, respectively. Similarly, the amount of aggregates (>250 \( \mu m \)) that survived slaking for 7-year switchgrass and cropped system are not significantly different; \( T_{15} + T_{25} \) is equal to 21.6 and 24.6 for 7-year switchgrass and cropped system, respectively. The water stable aggregates using the capillary-wetted pretreatment did not show any clear trend across the different types of vegetation. The mean weight diameter index is questionable when the aggregate size distribution is non-symmetrical (Six et al., 2000). The equation mean weight diameter \( MWD = \sum_{i=1}^{n} \bar{x}_i w \), also overestimates the original mean weight diameter for slaked pretreatment when five, fairly broad, size fractions are used (Kemper and Rosenau, 1986). From Tables 3 and 5 we observed that the mean weight diameter for the slaked pretreatment is sensitive to the amount of unstable macroaggregates (>250 \( \mu m \)). Why did this happen? We have shown that the slaking pretreatment produces a redistribution of unstable macroaggregate constituent units that, in turn, change the aggregate size distribution that determines the mean weight diameter to slaked pretreatment. This is further supported by the fact that mean weight diameter to capillary-wetted pretreatment did not show any clear trend across the different types of vegetations. We recall that the capillary-wetted pretreatment does not introduce any redistribution of unstable macroaggregates constituents. Therefore the mean weight diameter to slaked pretreatment are mainly determined by the redistribution of unstable macroaggregate constituents rather than by the amount of unstable macroaggregates, thus overestimating the mean weight diameter to slaked. We could expect that the mean weight
diameter to slaked, as indicator of soil stability, break down when we compare two soil samples with similar amount of unstable macroaggregates but different structural composition of unstable macroaggregates; the difference in structural composition can produce different redistribution pathways for unstable macroaggregate constituents. Breakdown of the mean weight diameter to slaked also can occur when we compare two soil samples with similar amounts of unstable macroaggregates and subtle differences between the qualities of the binding agents that keep unstable macroaggregate constituents bounded together.

**CONCLUSIONS**

We developed a theoretical framework that demonstrated that the use of a subsequent slaking following the slaked and capillary-wetted pretreatments provides the means for an accurate determination of the aggregate size distribution and the amount of stable and unstable macroaggregates. The amount and distribution of stable and unstable aggregates in the soil can be used as an indicator of the stabilization and destabilization of soil aggregates. These two mechanisms are closely associated with the dynamics of soil organic matter and soil quality. The total soil stability and soil stability indexes are suitable and highly sensitive to the effects of vegetation on soil stability. The total soil stability and the soil stability indexes were higher in soils under cool-season grass. These soils are well aggregated with the weighted average of stable aggregates representing 74%, of the dry weight of the soil followed by 55% under existing riparian forest, 38% under 7-year switchgrass and 36% under cropped system. The clearest difference was in the total amount of stable large
macroaggregates (>2000μm), which generally differed in the order cool-season grass > existing riparian forest > 7-year switchgrass = cropped system.

REFERENCES


Appendix

Why sand correction?

Although sand plays a passive role in the formation of aggregates it is widely recognized that the application of a correction for the amount of sand is essential for interpreting results on aggregate composition and dynamics. In general, sand could be in
three different forms in the soil: (1) sand that is within stable aggregates, (2) sand that is
within unstable aggregates and can easily be redistributed, and (3) sand that is free.

During fractionation, aggregate size classes will accumulate sand of similar
diameters. The accumulated sand particles can have two origins: particles of sand that result
from the destruction of macroaggregates (probably fine sand) and particles of sand that were
free and not within any aggregate. The redistribution of sand following the physical
separation of the aggregates (e.g., sieving) produces the so-called ‘loose sand’ effect
(Christensen, 1996; Cambardella and Elliott, 1993b; Elliott, 1986). The redistribution of
‘loose sand’ produces dispersion of carbon in the microaggregate size fraction (< 250 μm)
and the enrichment of clay and silt in macroaggregate-sized fractions (>250 μm). Although
the importance of sand is widely recognized, studies have not attempted to distinguish
experimentally between free sand particles and sand particles engaged in aggregates. We
analyzed the impact of the amount of sand in the whole soil on the sensitivity of the total soil
stability index (TSSI). We used \( f \) to represent TSSI without the sand correction and \( x \) to
represent TSSI with the sand correction. For simplicity and without losing generality, we
redefined the nomenclature as shown in equation [6].

\[
f = \frac{TS + Sand_{Stable\ Aggregates}}{TS + TU + Sand_{Whole\ Soil}} \quad \text{and} \quad x = \frac{TS}{TS + TU}
\]

[6]

In this equation TS is the total amount of stable aggregates, and TU is the total amount of
unstable aggregates. \( Sand_{Whole\ Soil} \) is the total amount of sand in the whole soil, and
\textit{Sand}_{\text{Stable Aggregates}} is the sand associated with stables aggregates. Note that \textit{Sand}_{\text{Stable Aggregates}} represents sand within stable aggregates and free sand with diameters similar to the aggregates.

The sensitivity \( \psi \) of \( f \) to changes in \( x \) is given by equation [7] and is strongly dependent on the total amount of sand \( \text{Sand}_{\text{Whole Soil}} \).

\[
\psi = \frac{\partial f}{\partial x} = (1 - \text{Sand}_{\text{Whole Soil}})^2 \tag{[7]}
\]

Figure 5 shows the values of \( \psi \) as a function of \( \text{Sand}_{\text{Whole Soil}} \). If \( \text{Sand}_{\text{Whole Soil}} = 0.5 \); then from equation [7] and from Figure 5 \( \psi \) is equal to 0.25. This means that a change of one unit in the value of the ratio \( TS/(TS + TU) \) could produce a relative change of 0.25 units in \( f \). We conclude from Figure 5 that not using the sand correction could mislead the interpretation of the results because the total amount of sand limits the sensitivity of \( f \) to reflect real changes in the ratio \( TS/(TS + TU) \). Therefore studying soil stability without the sand correction would mask significant differences between values of the soil stability index. The application of procedures for accounting for sand content becomes essential for correctly interpreting results on aggregate composition and dynamics.

**ACKNOWLEDGEMENTS**

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Table 1. General characteristics of the experimental field sites and surface soil (0-15 cm) properties

<table>
<thead>
<tr>
<th>Site</th>
<th>Taxonomic classification</th>
<th>Texture</th>
<th>TOC, [g kg⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cool season grass filter</td>
<td>Fine-loamy, mixed, superactive, mesic Cumulic Endoaquolls</td>
<td>Loam</td>
<td>33</td>
</tr>
<tr>
<td>Existing riparian forest</td>
<td>Fine-loamy, mixed, superactive, mesic Cumulic Haplaquudolls/</td>
<td>Sandy Loam / Loam</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Fine-loamy, mixed, superactive, mesic Cumulic Endoaquolls</td>
<td>Loam</td>
<td>21</td>
</tr>
<tr>
<td>7-year switchgrass filter</td>
<td>Fine-loamy, mixed, superactive, mesic Cumulic Endoaquolls</td>
<td>Loam</td>
<td>21</td>
</tr>
<tr>
<td>Cropped system</td>
<td>Fine-loamy, mixed, superactive, mesic Cumulic Endoaquolls</td>
<td>Loam</td>
<td>21</td>
</tr>
</tbody>
</table>

Table 2. Summary of the equations used to determine the aggregate size-stability distribution; $S$ stable aggregates, $U$ unstable aggregates, $G$ gain, $TS$ total percentage of stable aggregates, $TU$ total percentage of unstable aggregates, and $TG$ total gain; $T$ total percentage of soil aggregates, $T_{is}$ total amount of aggregates in fraction $i$ after slaked pretreatment, $T_{iss}$ total amount of aggregates in fraction $i$ after subsequent slaked treatment, $T_{icw}$ total amount of aggregates in fraction $i$ after capillary-wetted pretreatment.

<table>
<thead>
<tr>
<th>Size fraction, [μm]</th>
<th>Stable aggregates</th>
<th>Unstable aggregates</th>
<th>Gains</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 2000</td>
<td>$S_i = T_{is}$</td>
<td>$U_i = T_{icw} - T_{is}$</td>
<td></td>
</tr>
<tr>
<td>250 – 2000</td>
<td>$S_i = T_{iss}$</td>
<td>$U_i = T_{icw} - T_{iss}$</td>
<td>$G_i = T_{is} - T_{iss}$</td>
</tr>
<tr>
<td>53 – 250</td>
<td>$S_i = T_{icw}$</td>
<td></td>
<td>$G_i = T_{is} - T_{icw}$</td>
</tr>
<tr>
<td>&lt; 53</td>
<td>$S_i = T_{icw}$</td>
<td></td>
<td>$G_i = T_{is} - T_{icw}$</td>
</tr>
<tr>
<td>Totals</td>
<td>$TS = S_1 + S_2 + S_3 + S_4$</td>
<td>$TU = U_1 + U_2$</td>
<td>$TG = G_1 + G_2 + G_3 + G_4$</td>
</tr>
<tr>
<td>Eqs. to be check</td>
<td>$TS + TU = T$</td>
<td>$TU = TG$</td>
<td></td>
</tr>
<tr>
<td>Exp. test</td>
<td>$T_{iss} = S_1$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 3. The aggregate size-stability distribution under four different types of vegetation sites. Values are pooled data from 1997 and 1998 expressed as % dry weight of soil and on a sand-free basis ± 0.1 in each size fraction. Different letters indicate differences (P<0.05) between vegetation treatments within size classes. TS is the total percentage of stable aggregates and TU is the total percentage of unstable aggregates. T is total percentage of soil aggregates $T = TS + TU$.

<table>
<thead>
<tr>
<th>Size fraction</th>
<th>Water pretreatments</th>
<th>Aggregate Size-Stability Distribution</th>
<th>% dry weight of soil and on a sand-free basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>μm</td>
<td>Slaked</td>
<td>Capillary-wetted</td>
<td>Subsequent-Slaked</td>
</tr>
<tr>
<td>&gt; 2000</td>
<td>16.8</td>
<td>25.4</td>
<td>16.8a</td>
</tr>
<tr>
<td>250 - 2000</td>
<td>19.6</td>
<td>18.1</td>
<td>14.6a§</td>
</tr>
<tr>
<td>53 - 250</td>
<td>12.9</td>
<td>7.0</td>
<td>7.0a</td>
</tr>
<tr>
<td>&lt; 53</td>
<td>5.1</td>
<td>3.0</td>
<td>3.0a</td>
</tr>
<tr>
<td>Total</td>
<td>54.4</td>
<td>53.5</td>
<td>TS = 41.4</td>
</tr>
</tbody>
</table>

Cool Season Grass

| > 2000        | 9.5                 | 24.3              | 9.5b            | 14.8b  |
| 250 - 2000    | 21.5                | 14.0              | 9.8b            | 8.8b   | 4.1a     | 11.6  |
| 53 - 250      | 10.0                | 6.4               | 6.4a            | 3.6    |
| < 53          | 9.4                 | 6.0               | 6.0b            | 4.1    |
| Total         | 50.4                | 50.7              | TS = 31.7       | TU = 18.9b | 19.3 |

Existing Riparian Forest

| > 2000        | 2.8                 | 22.4              | 2.8c            | 19.6c  |
| 250 - 2000    | 20.3                | 14.5              | 11.0b           | 11.0b  | 3.5a     | 9.3   |
| 53 - 250      | 13.2                | 6.6               | 6.6a            | 6.6    |
| < 53          | 11.2                | 4.8               | 4.8a            | 6.4    |
| Total         | 47.5                | 48.3              | TS = 25.2       | TU = 23.1b | 22.3 |

7 year Switchgrass

| > 2000        | 2.1                 | 23.5              | 2.1c            | 21.3c  |
| 250 - 2000    | 22.4                | 18.0              | 11.0b           | 11.0b  | 7.0b     | 11.4  |
| 53 - 250      | 14.0                | 5.2               | 5.2a            | 8.1    |
| < 53          | 15.3                | 7.2               | 7.2b            | 8.1    |
| Total         | 53.8                | 53.9              | TS = 25.5       | TU = 28.3c | 27.6 |

Cropped system

§ Different letters within the same size class indicates differences (P <0.05) according to contrast separation test.
Table 4. Summary of indices proposed for assessing soil stability

<table>
<thead>
<tr>
<th>Index</th>
<th>Ref./Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean Weight Diameter:</strong> ( MWD = \sum_{i=1}^{n} \frac{x_i w_i}{\sum_{i=1}^{n} w_i} )</td>
<td>(van Bavel 1949) - Easier to calculate</td>
</tr>
<tr>
<td><strong>Geometric Mean Diameter:</strong> ( GMD = \exp\left[\frac{\sum_{i=1}^{n} w_i \log(x_i)}{\sum_{i=1}^{n} w_i}\right] )</td>
<td>(Mazurak 1950) - Extensive calculations</td>
</tr>
<tr>
<td><strong>Water Stable Aggregates:</strong> ( \text{WSA} = \frac{\text{weight of dry aggregates - sand}}{\text{weight of dry soil - sand}} \times 100 )</td>
<td>(Kemper 1966) (USDA 1998) - Useful when ( G2 = 0 )</td>
</tr>
<tr>
<td><strong>Aggregation Index:</strong> ( AI = 100 - DI )</td>
<td>(van Steenbergen, et al. 1991) - Whole soil sand correction</td>
</tr>
<tr>
<td><strong>Disruption Index:</strong> ( DI = \frac{DV}{DV_{\text{max}}} )</td>
<td>- Only gains are used</td>
</tr>
<tr>
<td>( DV_{\text{max}} = \frac{1}{n} \sum_{i=1}^{n}DV_{\text{max}} ) and ( DV = \frac{1}{n} \sum_{i=1}^{n}DV_{i} )</td>
<td>- Normalization with respect to the maximum disruption level possible</td>
</tr>
<tr>
<td><strong>Normalized Stability Index:</strong> ( NSI = 1 - \frac{DL}{DL_{\text{max}}} ) and ( DL = \frac{1}{n} \sum_{i=1}^{n}[(n+1)-i].DLS_{i} )</td>
<td>(Six, Elliott and Paustian 2000) - Slaked and capillary-wetted pretreatments</td>
</tr>
<tr>
<td>( DLS_{i} = \left[\frac{(P_{r}-S_{r})-(P_{o}-S_{o})}{2(P_{o}-S_{o})}\right] \left[\frac{(P_{r}-S_{r})-(P_{o}-S_{o})}{2(P_{o}-S_{o})}\right] )</td>
<td>- Need the sand size distribution</td>
</tr>
<tr>
<td>( DLS_{i}^{\text{max}} = \frac{1}{n} \sum_{i=1}^{n}[(n+1)-i].DLS_{i}^{\text{max}} )</td>
<td>- Correction for the aggregate-sized sand content.</td>
</tr>
<tr>
<td><strong>Total Soil Stability Index:</strong> ( TSSI = \frac{\sum_{j=1}^{n}[(n+1)-j]S_{j}}{\sum_{j=1}^{n}[(n+1)-j]T_{j}} ) and ( SSI = \frac{n \sum_{j=1}^{m}[(m+1)-j]S_{j}}{m \sum_{j=1}^{n}[(n+1)-j]T_{j}} )</td>
<td>Marquez et al. (this paper) - Based on size-stability distribution</td>
</tr>
<tr>
<td></td>
<td>- Slaked and capillary-wetted pretreatments, and subsequent-slake</td>
</tr>
</tbody>
</table>
Table 5. Values for the indices total soil stability index (TSSI), soil stability index (SSI) plots, water stable aggregates of slaked (WSAs) and capillary-wetted (WSAcw), mean weight diameter of slaked (MWDs) and capillary-wetted (MWDcw) soils under four different types of vegetation sites.

<table>
<thead>
<tr>
<th>Vegetation Type</th>
<th>TSSI</th>
<th>SSI</th>
<th>WSAs</th>
<th>WSAcw</th>
<th>MWDs, [mm]</th>
<th>MWDcw, [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cool Season Grass</td>
<td>0.74a</td>
<td>0.56a</td>
<td>0.67a</td>
<td>0.82a</td>
<td>1.98a</td>
<td>2.79a</td>
</tr>
<tr>
<td>Existing riparian forest</td>
<td>0.55b</td>
<td>0.37b</td>
<td>0.62a</td>
<td>0.76a</td>
<td>1.46b</td>
<td>2.73a</td>
</tr>
<tr>
<td>7 year Switchgrass</td>
<td>0.40c</td>
<td>0.21c</td>
<td>0.48b</td>
<td>0.83a</td>
<td>0.83c</td>
<td>2.91a</td>
</tr>
<tr>
<td>Cropped system</td>
<td>0.36c</td>
<td>0.18c</td>
<td>0.46b</td>
<td>0.77a</td>
<td>0.71c</td>
<td>2.56a</td>
</tr>
</tbody>
</table>

§ Different letter within a column indicate differences (P <0.05) according to contrast test.
Figure 1. Experimental procedure used to assess aggregate size-stability distribution
Figure 2. General pathways involved during the slaking pretreatment. $S$ stable aggregates, $U$ unstable aggregates, $G$ gain, $T_i$ total amount of aggregates in fraction $i$, and $T_{is}$ total amount of aggregates in fraction $i$ after slaked pretreatment.
Figure 3. General pathways involved during the capillary-wetted and the subsequent-slaked treatments. $S$ stable aggregates, $U$ unstable aggregates, $T_i$ total amount of aggregates in fraction $i$, $T_{icw}$ total amount of aggregates in fraction $i$ after capillary-wetted pretreatment $T_{iss}$ total amount of aggregates in fraction $i$ after subsequent slaked treatment.

\[
\begin{align*}
T_1 &= S_1 + U_1 \\
T_2 &= S_2 + U_2 \\
T_3 &= S_3 \\
T_4 &= S_4 \\
T_{icw} &= S_1 + U_1 \\
T_{2cw} &= S_2 + U_2 \\
T_{3cw} &= S_3 \\
T_{4cw} &= S_4 \\
T_{iss} &= S_1
\end{align*}
\]
Figure 4. Relationship between the mass of large macroaggregates >2000 μm quantified by slaked pretreatment ($T_{is}$) and stable large macroaggregates > 2000 μm quantified by subsequent-slaked treatment ($T_{iss}$). Values are expressed as % of soil dry and on a sand-free basis.

$y = (0.928)x - 0.870$

$r^2 = 0.9625$
Figure 5. Sensitivity of $f$ to changes in $TS/(TS+TU)$ as a function of the total amount of sand.
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the degree of deterioration, and predict threshold conditions before soil perturbations push an ecosystem away from its steady state condition.

INTRODUCTION

Although many studies have examined the effects of soil aggregates on soil water relations, root penetration and erosion potential only a few have examined the role of aggregates in controlling soil ecosystem (Elliot and Coleman, 1988; Jastrow et al., 1998). Stabilization and destabilization of soil aggregates involves a variety of physical, chemical, faunal, and microbial processes. In soils where structural stability is controlled by organic carbon, a link exists between organic carbon decomposition and soil aggregate dynamics (Golchin et al., 1998). Stabilization of soil aggregates and organic matter are intimately associated with each other. In aggrading systems organic inputs lead to the formation and stabilization of aggregates, which in turn can protect soil organic carbon from decomposition, leading to further aggregate stabilization. In soils at or near steady state, in terms of the amount of soil organic carbon in the whole soil, neither organic carbon nor aggregates are static, and the turnover of aggregates and various organic carbon pools are interrelated (Jastrow and Miller, 1998). On the other hand, destabilization is connected with a series of field process such as decomposition of organic binding agents, water content, slaking, growing cycles, intensive agriculture and deforestation. In degrading systems, the disruption of aggregates exposes previously protected but relatively labile organic carbon to decomposers, resulting in a loss of soil organic carbon and further destabilization of aggregates (Jastrow and Miller, 1998)
The size-stability distribution of soil aggregates at any given time is the result of a myriad of biological, physical, and chemical processes that change the soil structure at different scales and at different rates. It is widely accepted that the processes affecting soil aggregate dynamics occur relatively quickly and continuously under laboratory and field conditions (Kay, 1990; Terpstra, 1989). Several models of aggregation divide soil into macroaggregates (>250μm) and microaggregates (<250μm) (Tisdall and Oades, 1989). A conceptual approach that can be used to describe the concept of aggregate hierarchy was described by (Hadas, 1987) and (Dexter, 1988) and further developed by (Oades and Waters, 1991) and (Oades, 1993). A number of researches have presented an alternative view of aggregation in which microaggregates are formed within existing macroaggregates (Oades, 1984; Elliot and Coleman, 1988). Similarly a conceptual model was developed by Golchin et al (1998) which postulates that as particulate organic matter enters the soil from root or plant debris it becomes colonized by soil microbes and at the same time adsorbs mineral materials. This particulate organic matter is encrusted by mineral particles and becomes the organic core of stable microaggregates and is protected for rapid decomposition. Traditional approaches to studying soil aggregate dynamics include: (i) methods that compare aggregation and aggregate stability among soil types sometimes varying in texture or management history, and (ii) methods that explicitly incorporate time for studies of aggregation over long periods of time (Kay, 1998; Perfect et al., 1990b). Methods that compare aggregation and aggregate stability among soil types are normally restricted to a small number of soil types and do not explicitly include time as an independent variable. These methods are basically a qualitative analysis of the shape and changes of aggregate size distribution (Christensen, 1992). Methods that explicitly incorporate time into studies of aggregation are based on a conceptual model
proposed by Kay et al., 1988 (Kay, 1998; Perfect et al., 1990b). (Kay, 1998) proposed that: (i) changes in relative aggregate stability compared to a reference state are a function of changes in the concentration of stabilizing materials relative to their amount in the reference state and (ii) the changes in stabilizing materials are a function of time. Perfect et al., (1989) used this conceptual model to study temporal changes in water aggregate stability. (Perfect et al., 1990b) found that the empirical regression equation that best described their data was of the form: $WAS = WAS_{\text{max}} - Me^{bt}$ where $WAS$ and $WAS_{\text{max}}$ are the measured and maximum wet aggregate stabilities, respectively, $M$ is a constant that is a function of the water content; $M = WAS_{\text{max}} - WAS_{r_0}$, $b$ is the rate constant with typical values between 0.08 and 0.30 per year, and $t$ is time in years.

At present, there are no models and or analytical tools that integrate the aggregation, disruption, stabilization and destabilization processes in a framework that could make it reliable to study soil aggregate dynamics over time or in comparing aggrading, degrading or steady-state ecosystems. In order to correctly understand the complex dynamics of soil aggregation and stabilization, it is necessary to integrate all of the processes involved in soil aggregate dynamics. Consequently, such information can lead to improved approaches to soil management and minimize deterioration of the environment.

The objective of this study is to develop a conceptual model to study soil aggregate dynamics that integrate aggregation, disruption, stabilization, and destabilization processes of soil aggregates.
MATERIALS AND METHODS

Site description

Surface soils of the Coland series (fine-loamy, mixed superactive, mesic Cumulic Endoaquolls) from under three cool-season grass filters consisting of bromegrass (*Bromus inermis*), timothy (*Pheleum pratense*) and fescue (*Festuca* spp) were sampled. These filters are examples of the standard practice conservation filter (USDA-NRCS, 1997) and are located in the Bear Creek, Long Dick Branch, and Keigley Branch watersheds in north central Iowa, USA. Three sampling plots within each of the three cool-season filters were selected as part of an ongoing riparian research program (Schultz et al., 1995). A summary of the main properties of these soils is given in (Marquez, 2001).

Experimental design and soil sampling

The experimental design was a randomized complete block with plots approximately 20 x 30 m in size. Although, soil samples were collected once a month from May-November in 1997, and in early spring, mid-summer, and early fall in 1998, only samples for two months (July and August 1997) are used in this paper. We randomly collected 20 soil cores to a depth of 15 cm using a 5.6 cm steel coring bit. Soils samples were kept cool during transport and were stored in a refrigerator at 4 °C in the laboratory prior to processing and analysis.

Determination of the Aggregate Size Stability Distribution

The aggregate size-stability distribution SSD is determined following the protocol developed by (Marquez, 2001). Field-moist soil is passed through an 8-mm diameter sieve and air-dried. Two 100-g sub-samples of air-dried soil are used to determine the aggregate
size-stability distribution. One sub-sample is capillary-wetted to 5% soil moisture above field capacity and the other is left air-dry. The water pretreatments are referred as capillary-wetted (pre-wetted soil) and slaked (air-dry soil). Both sub samples are stored overnight in a refrigerator at 4 °C before wet sieving. Marquez’s protocol for the determination of the size-stability distribution includes capillary-wetting, slaking, and subsequent slaking to physically separate soil aggregates depending on their size and resistance to slaking into four size fractions: (i) fraction one (F1) large macroaggregates with diameters greater than 2000 μm, (ii) fraction two (F2) small-macroaggregates with diameters between 250-2000 μm, (iii) fraction three (F3) microaggregates with diameters between 53-250 μm, and (iv) fraction four (F4) mineral fraction with diameters smaller than 53 μm. After wet sieving the whole set of fractions are oven-dried at 70 °C. However, the large and small macroaggregates obtained by the capillary-wetted pretreatment are air-dried and used later for separation of stable macroaggregates. The amount of sand in each size fraction is determined by dispersion of a sub-sample of soil aggregate with sodium hexametaphosphate.

**Conceptual modeling of dynamics pathways for soil aggregates**

**The aggregation-disruption equation**

Soil aggregate dynamics are controlled by aggregation and disruption processes. Aggregation and disruption processes occur in many technologic and scientific situations and have been studied extensively by means of deterministic approximations using integral equations (Melzak, 1957; Drake, 1972) and discrete systems using differential equations (Ball and Carr, 1990). More recently stochastic model formulation has propelled feasible Monte
Carlo simulation methods that provide us with computational tools to rigorously derive deterministic solutions from a stochastic model (Eibeck and Wagner, 1998; Gueron, 1998).

Although aggregation and disruption processes have been studied extensively during the last century, there are serious limitations that restrict the generalization of theoretical achievements. Several factors contribute to the complexity of the problem. Critical factors are; time dependence rather than stationary processes, multi-particle processes rather than binary (including only two particles) processes, arbitrary particle shape rather than the idealized spherical particles, aggregation and disruption involving more than one type of particle, and finally the mass and/or density conservation are not necessarily fulfilled. From a mathematical point of view the aggregation-disruption process is described by a nonlinear differential equation as in equation [1]. The uniqueness and existence of the solution depends on the simplification of the critical factors mentioned above. Thus useful solutions have been reported in the literature (Drake, 1972). From physics point of view the differential equation describing the aggregation-disruption process was derived intuitively without rigorous mathematical analysis.

In soil we deal with aggregation and disruption of aggregates whose primary constituents are three types of particles, sand, silt, and clay. In addition, binding agents play important role in keep primary particles together. Processes affecting soil aggregates are not only dependent on time but also depend on a series of environmental factors. Thus, the rigorous modeling of soil aggregate dynamics is not a straightforward task. To address these difficulties, we present an illustrative visualization and conceptualization of the aggregation-disruption problem.
In our conceptualization we use the integral equation setting. The huge amount of soil aggregate constituent units supports the idea of using a continuum setting and a continuous distribution function. Although in our discussion we will use binary aggregation and disruption (where only two constituent units are involved); we do not lose generality in our conceptualization because it has been mathematically demonstrated that this setting is equivalent to disruption in multiple constituent units (McLaughlin et al., 1997; Piskunov, 1985).

The variation with time $t$ of the aggregate size distribution in systems with aggregation and disruption is defined by the kinetic equation [1].

$$\frac{\partial f(x,t)}{\partial t} = I(f;x,t) - O(f;x,t) \quad [1]$$

In this equation $x$ represents the size of the aggregate, $f(x,t)$ is the number of aggregates of size $x$ (x-aggregates) per unit volume; $I(f;x,t)$ denotes inputs that produces increments in the number of x-aggregates and $O(f;x,t)$ denotes outputs that produce a reduction in the number of x-aggregates.

**Inputs:** Two processes contribute to an increase in the number of x-aggregates per unit volume, the aggregation of smaller constituent units and the disruption of larger aggregates.

$$I(f;x,t) = I_{AL}(f;x,t) + I_{DU}(f;x,t) \quad [2]$$
\( I_{AL} (f; x, t) \) and \( I_{DU} (f; x, t) \) denote inputs due to the aggregation of aggregates from smaller size fractions (from lower size fractions) and inputs due to disruption of larger aggregates into smaller constituents (from upper size fractions), respectively.

\[
I_{AL} (f; x, t) = \frac{1}{2} \int_y^x f(y, t) f(x - y, t) A(y, x - y, t) \, dy \]  \hspace{1cm} [3]

\[
I_{DU} (f; x, t) = \int_x^\infty f(y, t) D(y, x, t) \, dy \]  \hspace{1cm} [4]

In these equations \( A(y, x - y, t) \) denotes the time dependent aggregation rate of aggregates of size \( y \) with aggregates of size \( x - y \). The time dependent rate at which aggregates of size \( x \) are produced from disruption of aggregates of size \( y \) is denoted by \( D(y, x, t) \).

**Outputs:** Two processes, the formation of larger aggregates by aggregation of \( x \)-aggregates and the disruption of \( x \)-aggregates into smaller constituent units can reduce the number of \( x \)-aggregates per unit volume.

\[
O(f; x, t) = O_{AU} (f; x, t) + O_{DL} (f; x, t) \]  \hspace{1cm} [5]

In equation [5], \( O_{AU} (f; x, t) \) denotes outputs due to aggregation that results in larger aggregates (to upper size fractions) and \( O_{DL} (f; x, t) \) denotes disruption that results in smaller aggregates (to lower size fractions).
The substitution of equations [7], [6], [4], and [3] in equation [1] leads to the full differential equation that describes the aggregation-disruption process.

**Calculation of the amount of aggregates in each fraction**

The solution of equation [1] provides the number of x-aggregates per unit volume at any time \( t(f(x,t)) \). The contribution of \( f(x,t) \) to the aggregate size distribution can be calculated by solving the following integral equation \( TA_i(t) = \int_0^\infty f(x,t)dx \). In this equation \( TA_i(t) \) is the total number of aggregate in fraction \( i \) at any time \( t \). \( TA_i(0) \) is the initial total number of aggregates in fraction \( i \). The smallest and largest aggregate sizes that define the boundary of the size fraction \( i \) are \( x_{\text{min}} \) and \( x_{\text{max}} \) (Figure 1). Thus the number of aggregates in size fraction \( i \) is determined by the competition between aggregation and disruption. If aggregation (disruption) predominates over disruption (aggregation) the number of aggregates in fraction \( i \) will increase (decrease) monotonically with time. The possibility of dynamic equilibrium between both competing processes also exists. In summary in equation [1] the local dynamics of aggregation, and disruption, which arise from
the underlying physics of what is being modeled, rule and are summed into the rate functions $A(x,z,t)$ and $D(y,x,t)$.

Dynamic loops and pathways for soil aggregates

The categorization of aggregates by size and the rate equation [1] allow the identification of dynamic loops and pathways for soil aggregates, (Figure 1). The soil aggregate dynamics model assess soil aggregation in terms of the aggregates size-stability distribution, which in addition to include the aggregates size distribution make a distinction between the amount of stable and unstable macroaggregates. The determination of the aggregates size-stability distribution involve the assumptions that soil aggregates can be categorized in terms of size and water stability. A thorough analysis of Figure 1 leads to the identification of a finite number of dynamic loops. The relevance of this result lies in the fact that the dominant dynamic pathway controls the capability, degradation, and recuperation of the soil. Thus, to maintain ecosystem health, the rate of aggregate formation needs to be higher or equal to the rate of aggregate disruption.

In steady-state ecosystem these pathways are interconnected and a continuous supply of particulate organic matter is required to maintain a given level of soil aggregation. The size of aggregate formed will depend of the quality and quantity of the particulate organic matter, presence of fungal hyphae, fine and very fine roots, and materials secreted by soil microorganisms. In steady-state systems where particulate organic matter is continually being added to the soil, the destruction of macroaggregates by decomposition of particulate organic matter is offset by the continual addition of new particulate organic matter. Thus, as the stability of a portion of the macroaggregates is decreasing due to the decomposition
process, other macroaggregates are being formed and stabilized, and in fact, the stabilization
of new macroaggregates may occur at the expenses of the breakdown of older less stable
macroaggregates (Golchin et al., 1998). In contrast, natural or human perturbations usually
push the ecosystem away from its steady-state condition, for example during tillage the
physical disturbance causes degradation of macroaggregates and releasing of
microaggregates. As a consequence the pathways associated with inputs of OM and
stabilization of large and small macroaggregates are broken e.g. loop 1 and loop 2 in Figure
1. Restoration managements will depend on the assessment of operating pathways. For
example in prairie soils where pathways associated with large macroaggregates (loop 1) have
been broken, but pathways associated with the biological capacity of the small
macroaggregates is functioning (loop 2), these soils under proper management can be
restored using vegetation with an adequate inputs and rate of organic matter decomposition
in order to restore loop 1 in short time.

In degrading systems aggregate disruption exposes particulate organic matter that has
been protected but relatively labile to decomposers, resulting in a loss amount of soil organic
matter and further destabilization of aggregates. These processes inhibit the establishment of
loop 1 and loop 2, which are related with the formation of stable large and small
macroaggregates, consequently, the aggregate size distribution shifted toward
microaggregates and fewer macroaggregates. As a consequence, of this inhibition result in
favor of processes related with loops 4, 5, and 6 which are related with the dynamic of
microaggregates that are more stable to be disrupted and the recuperation become too costly
and demanding long time.
Using the soil aggregate dynamics model the ecosystems can be monitored, the challenge is to maintain the dominant dynamic loops through appropriate management practices and thereby drive the dynamics of the soil aggregates with minimum ecological disruption to preserve the biological capacity that maintain the ecosystem sustainable.

**Model formulation**

Two scenarios are considered: (i) probing temporal variations of soil aggregates in the same ecosystem and soil unit and (ii) evaluating changes in soil aggregates in the same soil unit but in two ecosystems where one is the reference state and the other is the monitored ecosystem that has been subject to natural or human perturbations.

Soil aggregate dynamics are probed in terms of the processes that should take place in order to bring the system from a reference or initial state to a final or new state (Figure 2). Values in the aggregate size-stability distribution that are associated with the reference state will be identified using the subscript $n$ and values associated with the new state will be referenced using the subscript $n+1$. Details about the outcomes size aggregate distribution from slake, pre-wetted pretreatment and the subsequent slake of this soil, which was categorized by size, and stability are shown in (Table 2). For example $S_{2,n}$ and $S_{2,n+1}$ are the amount of stable aggregates in fraction two in the reference state and the new state, respectively.

Our approach includes three major steps: (i) the whole mass of unstable macroaggregates ($> 250 \, \mu m$) associated with the reference state is disrupted by a major perturbation such as slaking, (ii) aggregate constituent units that result from the disruption and stable aggregates from the reference state are allocated to size fractions belonging to the monitored state, and
(iii) the net change in the amount of aggregates in each size fraction that should occur in order to bring the system to the final state is calculated and interpreted in terms of allocation rules based on disruption and aggregation processes. In general, rules for aggregate allocation are based on three basic processes underlying the dynamics of soil aggregates: (i) disruption, (ii) stabilization/destabilization, and (iii) aggregation.

**Disruption:** Unstable macroaggregates (> 250 μm) can be fragmented during field perturbations and as a result their constituent units are redistributed into smaller size fractions. After fragmentation the constituent units of unstable large macroaggregates are allocated to size fractions two, three, and four. Similarly the constituent units of unstable small macroaggregates are redistributed into size fractions three and four (Figure 2). We know from the aggregates size-stability distribution (Marquez, 2001) that the mass of aggregates that can be gained in each size fraction by calculating the gains during the slaking process (Table 2), see equations [8], [9], and [10].

\[
b_{12}T_{1,n} = T_{2x,n} - S_{2,n} = G_{2,n} \quad [8]
\]

\[
b_{13}T_{1,n} + b_{23}T_{2,n} = T_{3x,n} - S_{3,n} = G_{3,n} \quad [9]
\]

\[
b_{14}T_{1,n} + b_{24}T_{2,n} = T_{4x,n} - S_{4,n} = G_{4,n} \quad [10]
\]

In these equations the parameter \( b_{ij} \) is the relative amount of unstable macroaggregates in fraction \( i \) (size fraction one or two) that can be disrupted and give rise to microaggregates in fraction \( j \) (size fraction two, three, or four), for example \( b_{12} \) is the relative amount of unstable macroaggregates in fraction one that after disruption give rise to new aggregates in fraction two. \( T_{1,n} \) and \( T_{2,n} \) are the total amount of stable plus unstable aggregates in size fraction one.
and two, respectively. \( T_{2n} \), \( T_{3n} \), and \( T_{4n} \) are the total amount of soils aggregates in size fraction two, three, and four after the slaking pre-treatment. \( S_{2n} \), \( S_{3n} \), and \( S_{4n} \) are the amount of stable aggregates in size fraction two, three, and four. \( G_{2n} \), \( G_{3n} \), and \( G_{4n} \) are the gains in size fraction two, three, and four after the slaking pre-treatment.

Unstable macroaggregates in size fraction one \( U_{1n} \) and in fraction two \( U_{2n} \) are the pools of aggregates at the reference state that can be disrupted and their constituent units distributed in smaller size fractions. Thus, the addition of \( U_{1n} \) and \( U_{2n} \) is equal to the summation of the gains, see equations [11], [12], and [13].

\[
(b_{12} + b_{13} + b_{14}) T_{1n} = U_{1n} \tag{11}
\]
\[
(b_{23} + b_{24}) T_{2n} = U_{2n} \tag{12}
\]
\[
U_{1n} + U_{2n} = G_{2n} + G_{3n} + G_{4n} \tag{13}
\]

**Stabilization/Destabilization:** The second process underlying the dynamics of soil aggregates is stabilization and destabilization of stable aggregates. Stable macroaggregates (>250 μm) can remain in the same size fraction from the reference state to the new state in two characteristic ways: (i) as stable macroaggregates, we call this process stabilization or (ii) as unstable macroaggregates, we call this process destabilization. Microaggregates, which by definition are stable, remain in the same size fraction as stable aggregates.

The amount of stable aggregates that remain in fraction \( j \) from the reference state to the new state is quantified through the parameter \( \delta_{j,n} \). This parameter is defined in equation [14] and illustrated in Figure 2.
Note that equation [14] quantifies the relative amount of stable aggregates that remain in each size fraction but does not establish any difference between the amounts of stable or unstable aggregates.

Comparison of the amount of stable aggregates at both reference and new states as well as assuming that there is a high probability that stable aggregates remain stable permit the calculation of the amount of aggregates that remain stable or unstable in size fraction one and two. For size fraction one, Table 1 summarizes the inquiring and equations used to calculate the amount of stable large macroaggregates that remain as stable \((a_1)\) or unstable \((b_1)\) large-macroaggregates. The information corresponding to size fraction two is given in Table 2. In Table 2, \(a_2\) is the amount of small macroaggregates that remain stable and \(b_2\), the amount of small macroaggregates that become unstable.

**Aggregation**: The other process underlying soil aggregate dynamics is aggregation. Small aggregate units (mineral particles, microaggregates, and/or small macroaggregates), can form larger macroaggregates. In order to assess the aggregation and disruption process we define the "net-flux" to each size fraction. The net-flux \((NF_{j,n+1})\) represents the net-flux of aggregates coming into or going out of size fraction \(j\). The net flux accounts for aggregates, that do not result from disruption of unstable macroaggregates nor from aggregates that remain in the same class from the previous state, see Figure 2. This concept is illustrated in equation [15] where we calculated the total amount of aggregates in fraction three as a

\[
\delta_{j,n} = \frac{S_{j,n}}{T_{j,n}}
\]
function of aggregates that remain in fraction three from the previous state \( S_{3n} \), the amount of aggregates that are gained from the disruption of macroaggregates \((b_{13}T_{1n} + b_{23}T_{2n})\), and the net-flux of aggregates to fraction three \( (NF_{3,n+1}) \).

\[
T_{3,n+1} = NF_{3,n+1} + S_{3n} + b_{13}T_{1n} + b_{23}T_{2n} \tag{15}
\]

We can show that \( S_{3n} + b_{13}T_{1n} + b_{23}T_{2n} = T_{3s,n} \), where \( T_{3s,n} \) is the amount of aggregates in size fraction three associated to the reference state after the slaking pre-treatment during the determination of the aggregate size-stability distribution. From equation \( 15 \) we estimated the net-flux to fraction three.

\[
NF_{3,n+1} = T_{3,n+1} - T_{3s,n} \tag{16}
\]

In general the net-flux in size fraction \( j \) associated with the new state \( (NF_{j,n+1}) \) is calculated using equation \( 17 \). In this equation, the net-flux is the difference between the total amount of aggregates \( (T_{j,n+1}) \) in fraction \( j \) associated with the new state and the amount of aggregates in fraction \( j \) associated with the reference state after the slaking pre-treatment.

\[
NF_{j,n+1} = T_{j,n+1} - T_{j,n} \tag{17}
\]
The net-flux is a number that can be positive or negative; positive values are interpreted as new aggregates coming into and negative values as aggregates going out of fraction $j$. Aggregates can come into fraction $j$ as a result of the aggregation of smaller aggregate constituent units or the disruption of larger aggregates (Figure 1). Similarly, aggregates can go out of fraction $j$ by aggregation and formation of new bigger aggregates or alternatively by the disruption and formation of smaller aggregates, (Figure 1). Typically we found that the value for the net-flux corresponding with the small fraction microaggregates and mineral fraction (<250 μm) were negative and the value for the net-flux corresponding with the larger fraction, macroaggregates (>250 μm) were positive. This is in agreement with the aggregation of smaller units resulting from the formation of macroaggregates.

Summation of all the net-fluxes should be equal or close to zero, owing to the fact that we use the same amount of soil.

$$\sum_{j=1}^{k} NF_{j,n+1} = TNF_{n+1} = 0$$  \[18\]

In equation [18], $TNF_{n+1}$ represent the total net-flux associated with the new state and $k$ is the total number of size fractions.

The net flux to fraction one can be expressed in terms of two components that build-up the total net flux; $x_i$ is the amount of stable large macroaggregates and $y_i$ the amount of unstable large macroaggregates (Figure 2). Thus $NF_{i,n+1} = x_i + y_i$. The values of $x_i$ and $y_i$ are calculated assuming that the amount of large macroaggregates associated with the new state ($S_{i,n+1}$) results from the addition of aggregates that remain from the reference state ($a_i$) and the amount of aggregates ($x_i$) going in/out as a result of further aggregation or
disruption; therefore \( x_1 = S_{1,n+1} - a_1 \). The same is valid for the amount of unstable large macroaggregates and \( y_1 = U_{1,n+1} - b_1 \). In these equations \( a_2 \) and \( b_2 \) are calculated from Table 1.

Similarly \( S_{2,n+1} = a_2 + x_2 \) and \( U_{2,n+1} = b_2 + y_2 \). In these equations \( a_2 \) and \( b_2 \) are calculated from Table 2. \( S_{2,n+1} \) and \( U_{2,n+1} \) are known from the aggregate SSD. Therefore \( x_2 = S_{2,n+1} - a_2 \) and \( y_2 = U_{2,n+1} - b_2 \) are the net-change of stable and unstable small macroaggregates, respectively. \( x_2 \) and \( y_2 \) can be expressed as the addition of two terms; one term is the contribution from \( G_{2,n} \) and the other from \( NF_{2,n+1} \). Thus \( x_2 = x_{2G} + x_{2NF} \) and \( y_2 = y_{2G} + y_{2NF} \), (Figure 2). In these equations \( x_{2G} \) is the amount of stable small macroaggregates (250–2000 \( \mu m \)) that result from the disruption of unstable large macroaggregates (>2000 \( \mu m \)). Similarly \( y_{2G} \) is the amount of unstable small macroaggregates that result from disruption of unstable large macroaggregates. Thus \( G_{2,n} = x_{2G} + y_{2G} \). Also \( x_{2,\text{NF}} \) and \( y_{2,\text{NF}} \) are the amount of stable and unstable macroaggregates that build-up the net flux \( NF_{2,n+1} \) thus \( NF_{2,n+1} = x_{2\text{NF}} + y_{2\text{NF}} \). The values of \( x_{2G} \) and \( y_{2G} \) are calculated assuming that the result of the disruption of \( U_{1,n} \) is mainly stable aggregate constituent units. In addition \( x_{2,\text{NF}} \) and \( y_{2,\text{NF}} \) are calculated assuming that the unstable aggregates are the main contributors to the \( NF_{2,n+1} \). For size fraction two, Table 3 summarizes the inquiries and equations used to calculate \( x_{3G} \), \( y_{2G} \), \( x_{2,\text{NF}} \), and \( y_{2,\text{NF}} \).
Monitoring Soil Aggregate Dynamics

In the following paragraphs we will define convenient indicators, which can be used to assess and monitor soil aggregate dynamics.

One, the maximum disruption of aggregates in a specific state is assessed through the disruption index \( DI \), which is defined in equation [19]. The disruption index is the relative amount of unstable macroaggregates (> 250 \( \mu \)m) with respect to the total amount of soil aggregates at the state been analyzed. For example at the reference or initial state \( DI \) is equal to:

\[
DI_n = \frac{U_{1,n} + U_{2,n}}{T_n}
\]

[19]

Two, after the perturbation that produces maximum disruption in the initial state of the system, the dynamics that lead to the new state is assessed through the possible values of the net-flux in each size fraction \( NF_{i,n+1} \). A summary of the possible values of \( NF_{i,n+1} \) and their interpretation is given in Table 4. To help the interpretation the reader is referred to Figure 1. It is important to bear in mind that the possible combination of processes coming from Table 4 defines the dynamics that lead to the new state of the system. The absolute aggregation and disruption leading to the new state is calculated from Table 5. In this table a plus sign represents positive values of the net-flux and a minus sign represents negative values of the net flux. \( A \) denotes aggregation and \( d \) denotes disruption.
Three, when $\text{NF}_{i,n+1} \geq 0$, $x_i \geq 0$, and $y_i \geq 0$ we define the following indexes (specific to fraction one): (i) the formation index of stable large macroaggregates $(FIS_{i,n+1})$ is defined in equation [20] as the relative amount of stable large-macroaggregates that result from the aggregation process, and (ii) the formation index of unstable large-macroaggregates is defined in equation [21].

\[
FIS_{i,n+1} = \frac{x_i}{\text{NF}_{i,n+1}} \quad \text{[20]}
\]

\[
FIU_{i,n+1} = \frac{y_i}{\text{NF}_{i,n+1}} \quad \text{or} \quad FIU_{i,n+1} = 1 - FIS_{i,n+1} \quad \text{[21]}
\]

In addition, to monitoring the stabilization and destabilization of stable large macroaggregates we define the following two indexes (specific for fraction one and when $S_{i,n} > 0$): (i) the index of destabilization of stable large-macroaggregates in size fraction one $(DSM_{i,n+1})$, is the relative amount of stable macroaggregates that remain in fraction one, that were stable in the reference state and became unstable in the “new” state, and (ii) the index of stabilization of stable macroaggregates in size fraction one $(SSM_{i,n+1})$, is the relative amount of stable large-macroaggregates that remain in size fraction one as stable macroaggregates in the new state.

\[
DSM_{i,n+1} = \frac{b_{i,n+1}}{S_{i,n}} \quad \text{[22]}
\]
$$SSM_{1,n+1} = \frac{a_{1,n+1}}{S_{1,n}} \quad \text{or} \quad SS_{1,n+1} = 1 - DSM_{1,n+1}$$ [23]

Four, in the same way that we did size fraction one, we can proceed with size fraction two and define a series of indexes specific for fraction two. Always that $G_{2,n} + NF_{2,n+1} > 0$, $x_{2,n+1} \geq 0$, and $y_{2,n+1} \geq 0$: (i) the formation index of stable small macroaggregates $FIS_{2,n+1} > 0$ is defined in equation [24] as the relative amount of stable small macroaggregates that result from disruption and aggregation, and (ii) the formation index of unstable small macroaggregates is defined in equation [25].

$$FIS_{2,n+1} = \frac{x_{2,n+1}}{\left( G_{2,n} + NF_{2,n+1} \right)}$$ [24]

$$FIU_{2,n+1} = \frac{y_{2,n+1}}{\left( G_{2,n} + NF_{2,n+1} \right)} \quad \text{or} \quad FIU_{2,n+1} = 1 - FIS_{2,n+1}$$ [25]

Note that $G_{2,n} + NF_{2,n+1} = T_{2,n+1} - S_{2,n}$. If $G_{2,n} + NF_{2,n+1} \leq 0$ the values of $FIU_{2,n+1}$ and $FIS_{2,n+1}$ are equal to zero. We should bear in mind that disruption of unstable large-macroaggregates from the reference state gives rise to new individual small-macroaggregates in the new state of the system. Also additional disruption and aggregation can give rise to new small macroaggregates.

We define the following two indexes, specific for fraction two and always that $S_{2,n} > 0$: (i) the index of destabilization of stable small macroaggregates $(DSM_{2,n+1})$, as the
relative amount of stable small macroaggregates that remain in fraction two, that were stable at the reference state and become unstable in the new state, (ii) the index of stabilization of stable small macroaggregates \( (SSM_{2,n+1}) \), as the relative amount of stable small macroaggregates that remain in size fraction two, that were stable at the reference state and remain stable in the new state.

\[
DSM_{2,n+1} = \frac{b_{2,n+1}}{S_{2,n}} \quad [26]
\]

\[
SSM_{2,n+1} = \frac{a_{2,n+1}}{S_{2,n}} \quad \text{or} \quad SSM_{2,n+1} = 1 - DSM_{2,n+1} \quad [27]
\]

When the amount of stable macroaggregates is equal to zero \( (DSM_{2,n+1}) \) and \( (SSM_{2,n+1}) \) are equal to zero.

For smaller size classes the formation index of stable aggregates is equal to one because microaggregates are, by definition, stable. Thus \( FIS_{3,n+1} = FIS_{4,n+1} = 1 \) and \( FIU_{3,n+1} = FIU_{4,n+1} = 0 \).

Five, in order to evaluate qualitatively and quantitatively the dynamics that lead to the new state of the system we define the aggregation-disruption index \( ADI (28) \). Qualitatively the sign of the \( ADI \) index points out if the dominant process that leads to the new state of the system was aggregation or disruption or neither of them. Quantitatively the \( ADI \) index is a number between \(-1\) and \(1\) \((-1 \leq ADI \leq 1\)) and gives the relative amount of aggregates that result from either aggregation and/or disruption dominant process.
In equation [28], \( A \) denotes the total amount of aggregates that result from aggregation and \( d \) the amount of aggregate constituent units that results from additional disruption; \( DI_n \) is defined in equation [19] and \( T \) is the total amount of soil after the sand correction; \( \alpha \) is defined in equation [29] and is the net amount of aggregates in fraction two that results from the disruption of unstable large macroaggregates and/or additional disruption and aggregation.

\[
ADI = \frac{[A + \alpha] - [DI_n + d]}{T} \tag{28}
\]

\[
\alpha = x_2 + y_2 \quad \text{if } NF_2 < 0 \quad \text{or } \alpha = G_2 \quad \text{if } NF_2 \geq 0 \tag{29}
\]

In equation [29] \( x_2 = x_{2G} + x_{2NF} \) and \( y_2 = y_{2G} + y_{2NF} \). When \( ADI > 0 \) means that the dominant process was aggregation, if \( ADI = 0 \) neither aggregation nor disruption dominate, and when \( ADI < 0 \) disruption is the dominant process that leads the system to the new state.

**RESULTS AND DISCUSSION**

**Model Evaluation (Experimental Application)**

To illustrate the use of our model we studied soil aggregate dynamics between July and August 1997 in soils from a cool-season filter consisting of bromegrass (\textit{Bromus inermis}), timothy (\textit{Pheleum pratense}) and fescue (\textit{Festuca spp}). The aggregate of July characterizes the initial state and the aggregate size-stability distribution of August characterizes the monitored (new state) of the system. The results from the slaking and capillary wetted
pretreatment as well as the respective aggregates size-stability distribution are shown in Table 6.

The results are expressed as percentage of the soil aggregate in each fraction after sand correction. The results indicate a higher amount of soil present as stable macroaggregates during August under cool-season grass (73.4%) compared to (62.1 %) under during July. Using the size-stability distribution protocol we were able to quantify the total amount of unstable macroaggregates. Table 6 shows that the amount of soil present as unstable macroaggregates is during July (25.7%) than (17.4%) during August. No difference was found between microaggregates and silt+clay between July and August under cool-season grass.

**Soil Aggregates Dynamics**

The results from the soil stability distribution were used in the soil aggregate dynamics model using the data collected in July and August under cool-season grass (Figure 3). Three basic processes underlie the dynamics of soil aggregates.

**Disruption** The disruption of unstable macroaggregates in July is allocated unevenly in size fractions two, three, and four in August. From the total disrupted, around 77% is allocated to fraction two and the other 23% is evenly distributed in fractions three and four. After disruption of unstable large macroaggregates, 77% was allocated as unstable small macroaggregates \( (y_{2G} = 10.2) \) and 23% was allocated as material \(<250 \mu m\) in fraction 3 and 4. The disruption of unstable small macroaggregates was allocated in F3 and F4 respectively.

**Stabilization/destabilization** Figure 3 shows that 100% \( (a_1 = 32.2) \) of stable large macroaggregates and 100% \( (a_2 = 29.9) \) of stable small macroaggregates remaining as stable in the same fraction from July to August. Therefore, none of the stable macroaggregates
were destabilized ($b_1 = 0$ and $b_2 = 0$). Microaggregates, which are by definition stable, remain in the same fraction, as stable aggregates.

**Aggregation** To assess aggregation and disruption the size-stability distribution model uses the net-flux. The net-flux is a number that can be positive or negative. Positive values are interpreted as new aggregates coming into and negative values as aggregates going out of fraction. Aggregates can come into a fraction as a result of the aggregation of smaller aggregate constituent units or the disruption of larger aggregates (Figure 2). Similarly, aggregates can go out of the fraction by aggregation and formation of new bigger aggregates or alternatively by the disruption and formation of smaller aggregates. Figure 3 shows that the net flux of large macroaggregates (>2000μm) is positive ($NF_1 = 22.8$), which results in formation of new stable large macroaggregates $x_1$ and formation of unstable large macroaggregates $y_1$ (Table 1). The newly formed large macroaggregates are mainly unstable large macroaggregates ($y_1 = 14.5$) and only ($x_1 = 8.2$) has been stabilized. In addition, $NF_2$ is negative ($NF_2 = -7.4$), the $NF_2$ results from $x_2$ and $y_2$, which are expressed as the addition of two terms; one term accounts for the contribution from $G_2$ and the other from $NF_2$. Thus $x_2 = x_{2G} + x_{2NF}$ and $y_2 = y_{2G} + y_{2NF}$, see Figure 2, Table 2 and Table 3. In these equations $x_{2G}$ is the amount of stable small macroaggregates (250–2000 μm) that result from disruption of unstable large macroaggregates (>2000 μm). Similarly $y_{2G}$ is the amount of unstable small macroaggregates that result from disruption of unstable large macroaggregates thus, $G_{2x} = x_{2G} + y_{2G}$. Also $x_2$ and $y_2$ are the amount of stable and unstable macroaggregates that build-up the net flux $NF_2$ thus $NF_2 = x_2 + y_2$. Disruption of
the unstable large macroaggregates resulted in a total gain \( G_{2,n} = 13.4 \) of small macroaggregates, which are allocated in F2 (250-2000 μm), however only \( x_{2G} = 3.1 \) of these were allocated as stable small macroaggregate and the rest were allocated as unstable small macroaggregates \( y_{2G} = 10.2 \). In addition, Figure3 and Table 3 show that \( x_{2,NF} = 0 \) and \( y_{2,NF} = -7.4 \) and they are the amount of stable and unstable macroaggregates that build-up the net flux \( NF_2 \). Thus, \( NF_2 = x_{2,NF} + y_{2,NF} \) and \( NF_2 = -7.4 \). The

\[
NF_3 = S_{3,n+1} - (S_{3,n} + G_{3,n}) \quad \text{and} \quad NF_3 = -8.5.
\]

\[
NF_4 = S_{4,n+1} - (S_{4,n} + G_{4,n}) \quad \text{and} \quad NF_4 = -7.2.
\]

These results indicate that small macroaggregates \( NF_2 = -7.4 \) get together with microaggregates \( NF_3 = -8.5 \) and silt+clay particles \( NF_4 = -7.2 \) to form new large macroaggregates, which is reflected in a positive net-flux of large macroaggregates to F1 \( NF_1 = 22.8 \).

**Monitoring Aggregates Dynamics**

The soil aggregates dynamics model use indicators to assess and monitor soil aggregate dynamics:

**Disruption index (DI)** is the relative amount of unstable (>250 μm) with respect to the total amount of soil aggregates at the reference state. Table 7 shows that DI = 0.26 in July and the DI = 0.17 in August under CSG. The results indicate that 26% and 17% of the unstable macroaggregates underwent disruption and formed smaller aggregates during July and August respectively under CSG.
Formation indices (FIS or FIU) the result of this formation process are related to the formation of stable (FIS) or unstable (FIU) macroaggregates. From July to August there is a substantial formation of stable small macroaggregates \( FIS_{2,n+1} = 0.52 \) compared to the formation of stable large macroaggregates \( FIS_{1,n+1} = 0.36 \); however, the formation of large unstable macroaggregates \( FIU_{1,n+1} = 0.64 \) is larger than the formation of small unstable macroaggregates \( FIU_{2,n+1} = 0.48 \).

Stabilization and Destabilization indices (SSM and DSM) Stable large and small macroaggregates remain as stable aggregates in August and none of them become unstable. This is supported by the values of the \( SSM_{1,n+1} = 1 \) and \( DSM_{1,n+1} = 0 \) for fraction one, and \( SSM_{2,n+1} = 1 \) and \( DSM_{2,n+1} = 0 \) for fraction two in Table 7.

The total Aggregation-Disruption Index (ADI) After the total disruption of unstable macroaggregates in July the dominant process responsible for the aggregate SSD in August was aggregation \( A = 0.23 \) contrary to the result of additional disruption \( D = 0 \). The aggregation-disruption index \( ADI \) is positive and its magnitude is equal to 0.031, which means that there was a net aggregation of 3.1%. The ADI point out that during July-August the dominant process is aggregation.

In addition, Figure 3 showed that the predominant loops that is controlling this natural ecosystem, which consists of bromegrass, timothy and fescue. Species with extensive fine and very fine root system and higher dead fine root biomass as a consequence in this long establish cool-season grass, particulate organic matter is continually added to the soil, the destruction of macroaggregates by decomposition of particulate organic matter is
counterbalance by the continual addition of new particulate organic matter. Thus, as the stability of a portion of the macroaggregates is decreasing due to decomposition process, other macroaggregates are being formed and stabilized.

**CONCLUSIONS**

We developed a new theoretical and conceptual framework for studying soil aggregate dynamics using the soil aggregate dynamics model, which integrates aggregation, disruption, stabilization, and destabilization of soil aggregates. The model uses the aggregate size-stability distributions associated with two states of the system, the reference and the probing state. A number of convenient indicators are developed to assess aggregation, disruption, stabilization, and destabilization of soil aggregates. The predominant process driving the system from the reference state to the new state is identified and quantified through the aggregation-disruption index. Similarly, dynamic loops for soil aggregates were identified.

To validate our model we studied soil aggregate dynamics between July and August 1997 in soils from a cool-season grass filter. The model exercise shows that there was a net aggregation of 3.1% during July-August and the aggregation process drives soil aggregate dynamics from July to August. The soil aggregates dynamics model provides a convenient approach for studies of soil aggregate dynamics. It can also be used to monitor changes, due to effects of vegetation or management practices aggregation, stabilization, and destabilization of soil aggregates.
REFERENCES


Figure 1. Dynamics lops and pathways for soil aggregates. In this equation $x$ represents the size of the aggregate, $f(x,t)$ is the number of aggregates of size $x$ (x-aggregates) per unit volume; $I(f;x,t)$ denotes inputs that produces increments in the number of x-aggregates and $O(f;x,t)$ denotes outputs that produce a reduction in the number of x-aggregates.

Loops
1. $O_1$- $I_2$- $O_2$- $I_1$
2. $O_1$- $I_2$- $O_2$- $I_3$- $O_3$- $I_2$- $O_2$- $I_1$
3. $O_1$- $I_2$- $O_2$- $I_3$- $O_3$- $I_4$- $O_4$- $I_3$- $O_3$- $I_2$- $O_2$- $I_1$
4. $O_2$- $I_3$- $O_3$- $I_2$
5. $O_2$- $I_5$- $O_3$- $I_4$- $O_4$- $I_3$- $O_3$- $I_2$
6. $O_5$- $I_4$- $O_4$- $I_3$
7. $O_1$- $I_3$- $O_3$- $I_1$
8. $O_1$- $I_4$- $O_4$- $I_1$
9. $O_2$- $I_4$- $O_4$- $I_2$
Figure 2. Dynamic pathways of soil aggregates described by the soil aggregate dynamics model. \(S\) = stable aggregates, \(U\) = unstable aggregates, \(NF\) = net flux, \(G\) = gain, \(x\) = new stable macroaggregates when \(NF > 0\), \(y\) = new unstable macroaggregates when \(NF > 0\), \(a\) = stable macroaggregates that remain stable, and \(b\) = stable macroaggregates that became unstable, \(n\) = reference state, \(n+1\) = new state.
Figure 3. Dynamic pathways of aggregates under cool-season grass filter using data from July and August 1997. Values are expressed on sand-free basis % of soil aggregates in size fractions. S = stable aggregates, U = unstable aggregates, NF = net flux, G = gains, x = new stable macroaggregates when NF > 0, y = new unstable macroaggregates when NF > 0, a = stable macroaggregates that remain stable, and b = stable macroaggregates that became unstable.
Table 1. Inquiries and equations used in calculating the amount of stable and unstable large macroaggregates, \( S \) = stable aggregates, \( a \) = stable macroaggregates that remain stable, \( b \) = stable macroaggregates that became unstable, \( n \) = reference state, \( n+1 \) = new state.

<table>
<thead>
<tr>
<th>( S_{1,n} )</th>
<th>Inquiry</th>
<th>( S_{1,n} )</th>
<th>Inquiry</th>
<th>( S_{1,n} )</th>
<th>Inquiry</th>
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<tr>
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<td>( S_{1,n} )</td>
<td>( S_{1,n} )</td>
<td>( S_{1,n} &gt; S_{1,n+1} )</td>
<td></td>
</tr>
<tr>
<td>( a_1 )</td>
<td>( 0 )</td>
<td>( 0 )</td>
<td>( 0 )</td>
<td>( 0 )</td>
<td>( S_{1,n} - S_{1,n+1} )</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Inquiries and equations used in calculating the amount of stable and unstable small macroaggregates, \( S \) = stable aggregates, \( a \) = stable macroaggregates that remain stable, \( b \) = stable macroaggregates that became unstable, \( n \) = reference state, \( n+1 \) = new state.

<table>
<thead>
<tr>
<th>( S_{2,n} )</th>
<th>Inquiry</th>
<th>( S_{2,n} )</th>
<th>Inquiry</th>
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<th>Inquiry</th>
<th>( S_{2,n} )</th>
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</thead>
<tbody>
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<td>( 0 )</td>
<td>( S_{2,n} )</td>
<td>( S_{2,n} )</td>
<td>( S_{2,n} )</td>
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</tr>
<tr>
<td>( a_2 )</td>
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<td>( 0 )</td>
<td>( 0 )</td>
<td>( S_{2,n} - S_{2,n+1} )</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Inquiries and equations used in calculating the amount of stable and unstable small macroaggregates, \( G \) = gains, \( x \) = new stable macroaggregates, \( y \) = new unstable macroaggregates.

<table>
<thead>
<tr>
<th>( x_{2G} )</th>
<th>( y_{2G} )</th>
<th>( x_{2NF} )</th>
<th>( y_{2NF} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(</td>
<td>x_2</td>
<td>- G_2 \geq 0 )</td>
<td>( G_{2,n} )</td>
</tr>
<tr>
<td>(</td>
<td>x_2</td>
<td>- G_2 &lt; 0 )</td>
<td>(</td>
</tr>
</tbody>
</table>
Table 4. Controlling process depending on the sign of the net-flux. \( I(f;x,t) \) denotes inputs that produces increments in the number of \( x \)-aggregates and \( O(f;x,t) \) denotes outputs that produce a reduction in the number of \( x \)-aggregates.

<table>
<thead>
<tr>
<th>Net-flux</th>
<th>Controlling process</th>
</tr>
</thead>
<tbody>
<tr>
<td>( NF_1 &lt; 0 )</td>
<td>( O_{DL} (f;x,t) )</td>
</tr>
<tr>
<td>( NF_2 &lt; 0 )</td>
<td>( O_{DL} (f;x,t) + O_{AU} (f;x,t) )</td>
</tr>
<tr>
<td>( NF_3 &lt; 0 )</td>
<td>( O_{DL} (f;x,t) + O_{AU} (f;x,t) )</td>
</tr>
<tr>
<td>( NF_4 &lt; 0 )</td>
<td>( O_{AU} (f;x,t) )</td>
</tr>
<tr>
<td>( NF_1 &gt; 0 )</td>
<td>( I_{AL} (f;x,t) )</td>
</tr>
<tr>
<td>( NF_2 &gt; 0 )</td>
<td>( I_{AL} (f;x,t) + I_{DU} (f;x,t) )</td>
</tr>
<tr>
<td>( NF_3 &gt; 0 )</td>
<td>( I_{AL} (f;x,t) + I_{DU} (f;x,t) )</td>
</tr>
<tr>
<td>( NF_4 &gt; 0 )</td>
<td>( I_{DU} (f;x,t) )</td>
</tr>
</tbody>
</table>
Table 5. Dynamic pathways and absolute aggregation and disruption, $A = \text{aggregation}$

\[ d = \text{disruption}, \]

<table>
<thead>
<tr>
<th>$NF_1$</th>
<th>$NF_2$</th>
<th>$NF_3$</th>
<th>$NF_4$</th>
<th>$A$</th>
<th>$d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>$</td>
<td>NF_4</td>
</tr>
<tr>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>$NF_1 + NF_2$</td>
<td>0</td>
</tr>
<tr>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$NF_1$</td>
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<td>-</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>$</td>
</tr>
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<td>+</td>
<td>0</td>
<td>$</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>0</td>
<td>$NF_4$</td>
</tr>
<tr>
<td>+</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>$NF_1$</td>
<td>$NF_3 + NF_4$</td>
</tr>
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<td>-</td>
<td>-</td>
<td>+</td>
<td>$NF_1$</td>
<td>$NF_4$</td>
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<tr>
<td>-</td>
<td>+</td>
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<td>-</td>
<td>$</td>
<td>NF_4</td>
</tr>
<tr>
<td>-</td>
<td>+</td>
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<td>-</td>
<td>$</td>
<td>NF_3</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>$</td>
<td>NF_4</td>
</tr>
<tr>
<td>+</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>$NF_1 + b*</td>
<td>NF_4</td>
</tr>
</tbody>
</table>

*b is a constant to be determined.
Table 6. The aggregate size-stability distributions under long establish cool season filter data from July and August 1997. Values are expressed on sand-free basis % of soil aggregates in size fractions. Different letter indicate differences (P<0.05) between vegetation treatments within size class.

<table>
<thead>
<tr>
<th>Size fraction μm</th>
<th>Water pretreatments</th>
<th>Aggregates. Size-Stability Distribution (SSD)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Slaked</td>
<td>Capillary-wetted</td>
</tr>
<tr>
<td>&gt; 2000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>250 - 2000</td>
<td>32.2</td>
<td>49.5</td>
</tr>
<tr>
<td>53 - 250</td>
<td>13.7</td>
<td>7.3</td>
</tr>
<tr>
<td>&lt; 53</td>
<td>11.2</td>
<td>5.3</td>
</tr>
<tr>
<td>Total</td>
<td>100.4</td>
<td>100.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt; 2000</td>
<td>40.4</td>
<td>54.9</td>
</tr>
<tr>
<td>250 - 2000</td>
<td>40.3</td>
<td>35.9</td>
</tr>
<tr>
<td>53 - 250</td>
<td>10.4</td>
<td>5.2</td>
</tr>
<tr>
<td>&lt; 53</td>
<td>8.9</td>
<td>4.0</td>
</tr>
<tr>
<td>Total</td>
<td>100.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>
Table 7. Indicators of soil aggregate dynamics. FIS = formation index of stable macroaggregates, FIU = formation index of unstable macroaggregates, DSM Index of destabilization of macroaggregates, SSM = Stabilization of stable macroaggregates, \( x_2 \) = net-change of stable macroaggregates, \( y_2 \) = net-change of unstable macroaggregates, DI = disruption index, A = represents the amount of aggregates that result from aggregation, d = disruption, ADI = aggregation-disruption index.

<table>
<thead>
<tr>
<th>Size Fraction</th>
<th>FIS</th>
<th>FIU</th>
<th>DSM</th>
<th>SSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 2000 ( \mu m )</td>
<td>0.36</td>
<td>0.64</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>250 – 2000 ( \mu m )</td>
<td>0.52</td>
<td>0.48</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( x_2 )</th>
<th>( y_2 )</th>
<th>DI</th>
<th>A</th>
<th>d</th>
<th>ADI</th>
</tr>
</thead>
<tbody>
<tr>
<td>July</td>
<td>26</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>August</td>
<td>3.1</td>
<td>2.9</td>
<td>17</td>
<td>22.7</td>
<td>0</td>
</tr>
</tbody>
</table>
EVALUATING SOIL DEGRADATION UNDER CROPPED SYSTEM USING A LONG ESTABLISHED RIPARIAN COOL-SEASON AS REFERENCE STATE

A paper to be submitted to the Soil Science Society of America Journal

C.O. Marquez, C.A. Cambardella, R.C. Schultz, and T.M. Isenhart

ABSTRACT

Riparian buffers can potentially increase soil carbon sequestration and enhance surface water quality in the intensively-row-cropped upper Midwest, USA. Grass buffer systems provide year-round soil cover, limiting erosion and favoring soil development processes by improving soil organic matter sequestration and soil aggregation. The purpose of this study was to evaluate the effect of row crop agriculture on soil degradation through the quantification of total, light, and heavy soil carbon and to study soil aggregate dynamics and carbon associated with aggregates in a long established riparian cool-season grass filter, and a non-buffered annual row cropped riparian zone in central Iowa, USA. The soil aggregate dynamics model was used to analyze aggregate dynamics and carbon associated with aggregates. Pooled data from 1997 and 1998 showed higher amounts of large and small stable macroaggregates in the cool season grass filter than in the cropped field. The net process that leads to new state annual row cropped is disruption, which result in the disruption of 19% of the aggregates. This disruption of macroaggregates exposes previously protected labile organic carbon to decomposers, resulting in a loss of 11.3 mg C g⁻¹ and further destabilization of macroaggregates. The amount of total particulate organic C was three times greater in cool-season grass vs. crop and accounted for 16% of the total organic carbon under cool season grass and 7% under cropped field. The results indicate that
macroaggregates under cool-season grass are more stable and provide an important mechanism for C sequestration and support the higher amounts of light and heavy particulate organic matter than cropped system.

INTRODUCTION

Agriculture in the Midwestern United States has removed most native ecosystems from the landscape. The loss of these ecosystems has increased the potential for non-point source pollution of surface and groundwater systems. Especially critical to the processes of surface water quality protection is the riparian ecosystem of a stream. Native riparian ecosystems trap sediments from surface runoff, allow water to infiltrate into the soil, and then use the nutrients and chemicals in solution during growth (Schultz et al., 1995).

When the riparian zone is cleared for row crop farming or intensive grazing there is no longer a buffer zone to protect the stream from non-point source pollution (Schultz et al., 1995). Soil degradation is a severe global issue, and predominant degradative processes are accelerated erosion, depletion of soil organic matter and plant nutrients, and a decline in soil structure (Lal, 2000).

Considerable attention has recently been focused on the restoration of riparian forests and grass buffer systems to filter sediment, nutrients, and pesticides entering from upslope agricultural fields (Hubbard and Lowrance, 1996). Forests reduce erosion by improving water infiltration, intercepting rain and snow thereby reducing the impacts of water droplets, and by physically stabilizing soil with their roots and leaf litter. Perennial grasses reduce water runoff, sediment loss and help soil development processes by improving soil organic matter, soil structure, and soil water and nutrient-holding capacity (Kort et al., 1998).
The functioning of soil is profoundly influenced by its organic matter content. The ability of a soil to supply nutrients, store water, release greenhouse gases, modify pollutants, resist physical degradation, and produce crops within a sustainably managed framework are all strongly affected by the quality and quantity of the organic matter (Ress et al., 2000).

In soils at or near equilibrium in terms of the amount of soil organic matter in the whole soil, neither organic matter nor aggregates are static, and the turnover of aggregates and various organic matter pools are still interrelated. In contrast, in degrading systems, the disruption of aggregates exposes previously protected but relatively labile organic matter to decomposers, resulting in a loss of soil organic matter and further destabilization of aggregates. In any case, the feedback between soil organic matter cycling and aggregate cycling appears to be controlled by the formation and destruction of organomineral associations functioning as aggregate binding agents (Jastrow and Miller, 1998). Cultivation of the soil results in a rapid but relatively short-lived loss of organic C followed by the establishment of a new steady state (Janzen et al., 1998).

Organic matter is both a source and a sink for plant nutrients, and provides an energy substrate for soil organisms (Carter, 2000). The positive interrelationship between soil organic matter and soil aggregation has important benefits on both water and air infiltration, soil erodibility and conservation of organic matter and nutrients (Feller and Beare, 1996). Stable macroaggregates consist of microaggregates held together by roots and fungal hyphae. They form readily in soil where organic residues have been added to soil, especially where the soil already contains large amounts of stable microaggregates. Macroaggregates are readily disrupted by tillage or heavy rain, when exposed organic matter is oxidized (Tisdall, 1996).
Aggregates are generally physically separated by wet techniques (Kemper and Rosenau, 1984). However, care must be taken in interpreting such results on the type of organic matter associated with microaggregates of different sizes, since organic materials and mineral soil may be re-distributed (Tisdall, 1996). Marquez (2001) presented a new theoretical and experimental framework that permits an accurate determination of aggregate size-stability distribution, which in addition to estimating aggregate size distribution distinguishes between the amounts of stable and unstable macroaggregates. This conceptual framework eliminates misinterpretation induced by traditional approaches and is a valuable tool for monitoring soil aggregate dynamics and carbon associated with aggregates, which in turn play an important role in maintaining ecosystem sustainability. Although difficulties still remain in defining sustainability (Ress et al., 2000) there is a consensus, that organic matter has a significant role in the sustainability of an ecosystem (Switt and Woomer, 1993). But, because soil aggregation and soil organic matter are intimately associated with each other (Jastrow and Miller, 1998). An understanding of soil aggregation, stabilization, and destabilization, along with the carbon fractions associated with the aggregate fractions is needed to evaluate the soil degradation process.

These studies are important in developing indices that can be used to determine present soil health, assess degrees of soil deterioration, and predict threshold conditions before a soil or ecosystem “goes over the brink” of ecological deterioration (Miller, 1998). Although many studies have examined the effects of soil aggregates on soil water relations, root penetration, and erosion potential only a few have examined the role of aggregates in controlling the soil ecosystem (Elliot and Coleman, 1988). Knowledge of the processes and dynamics of soil aggregation, and the relationship between soil aggregates and soil quality is
needed for developing appropriate indices and management systems that enhance soil function and sustainability (Lal, 2000). We present a conceptual model of soil aggregate dynamics, which is based on our previous work. This model integrates the aggregation, disruption, stabilization, and destabilization processes of soil aggregates in a framework that permits studying soil aggregate dynamics over time or comparing ecosystems such as aggrading, degrading or steady-state systems (Marquez, 2001).

The objective was to study the dynamics of soil aggregates and the associated organic carbon in aggregates, and biologically active organic matter fractions under a cropped system using a long established riparian cool-season as a reference state.

MATERIALS AND METHODS

Site Description

The study sites are located within the small adjacent Bear Creek, Long Dick Branch, and Keigley Branch watersheds in north-central Iowa, USA. The primary land use of the three watersheds is corn-soybean row crop production or intensive grazing. The plots were located on long established riparian cool-season grass filters, and cropped fields along all three creeks. Within each plot we sampled sites on similar, moderately drained soils on the alluvial floodplain where the dominant soil type is Coland (Fine-loamy, mixed, superactive, mesic Cumulic Endoaquolls) (Dewit, 1984).

Experimental Design and Soil Sampling

The experimental design was a randomized complete block with three blocks (streams) and two treatments (vegetation types). Each treatment combination contained three plots that
were approximately 20 x 30 m in size. Surface soils were collected once a month from May to November in 1997, and in early spring, midsummer, and early fall in 1998. We randomly collected 20 soil cores within each plot to a depth of 15 cm using a 5.6 cm steel coring bit for half of the cores and a 2.5 cm bit for the remaining 10 cores. The 10 cores taken with the larger diameter bit were pooled to form one composite sample from each plot. This sample that was used to quantify aggregate size distributions and aggregate-associated C. The 10 cores taken with the smaller diameter bit were pooled into one composite sample and used to quantify soil organic matter fractions. Soil samples were kept cool during transport and were stored in a refrigerator at 4 °C prior to processing and analysis.

**Determination of the Aggregate Size Stability Distribution**

The aggregate size-stability distribution is determined following the protocol developed by Marquez (2001). Field-moist soil is passed through an 8 mm diameter sieve and air-dried. Two 100 g sub-samples of air-dried soil are used to determine the aggregate size-stability distribution. One sub-sample is capillary-wetted to 5 % soil moisture above field capacity and the other is left air-dry. The water pretreatments are referred to as capillary-wetted (pre-wetted soil) and slaked (air-dry soil). Both sub samples are stored overnight in a refrigerator at 4 °C before wet sieving. The protocol for the determination of the size-stability distribution includes capillary-wetting, slaking, and subsequent slaking to physically separate soil aggregates into four size fractions: i) fraction one (F1) large macroaggregates with diameters greater than 2000 μm, ii) fraction two (F2) small-macroaggregates with diameters between 250-2000 μm, iii) fraction three (F3) microaggregates with diameters between 53-250 μm, and iv) fraction four (F4) mineral fraction with diameters smaller than
53 μm. After wet sieving the whole set of fractions are oven-dried at 70 °C. However, the large and small macroaggregates obtained by the capillary-wetted pretreatment, are air-dried and later used for separation of stable macroaggregates. The amount of sand in each size fraction is determined by dispersion of a sub-sample of soil aggregate with sodium hexametaphosphate. The aggregate fractions are ground on a roller mill to pass a 250 μm sieve and stored at room temperature. After removal of carbonates, total organic C is quantified using a Carlo-Erba NA 1500 CN analyzer (Haake Buchler Instruments, Paterson, NJ, USA).

**Fractionation of Light and Heavy Organic Matter**

Light organic matter (LPOM) and heavy organic matter (HOM) are separated following the experimental method reported by Cambardella and Elliott, (1993a) and Gale et al., (2000). Field-moist soil is passed through a 2 mm diameter sieve, the larger pieces of stubble and roots are removed by hand, and the soil is air-dried. A 30 g sub-sample is dispersed with 100 mL of 5 g L⁻¹ sodium hexametaphosphate by shaking 15 hr on a reciprocal shaker. The dispersed soil samples are passed through a 53 μm sieve and rinsed several times with DI water. The material retained on the 53 μm sieve is back-washed onto a 20 μm nylon filter and a vacuum is applied to remove excess water. The material is then rinsed into a 100 mL beaker with sodium polytungstate (1.85 g cm⁻³) to a volume of 50 mL. The samples are allowed to separate overnight at room temperature. The following day, the floating LPOM is aspirated, washed several times with water on a 20 μm nylon filter, and dried at 50 °C. The material that did not float at a density of 1.85 g cm⁻³ is back-washed onto a 20 μm nylon filter and washed several times with water. The material is rinsed into a 100 mL beaker with
sodium polytungstate (2.22 g cm$^{-3}$) and allowed to separate overnight at room temperature. The floating material HPOM is aspirated, washed, and dried at 50 °C. Both fractions are finely ground and C is quantified with a Carlo-Erba NA 1500 CN analyzer. Total soil organic C is determined on finely ground sub-samples of 2 mm air-dried soil.

**Microscopic Observations and Chemical Composition of Organic Matter**

Aggregates were examined using scanning electron microscopy (SEM). For SEM observations, aggregates were mounted on graphite stubs, and coated with gold under vacuum in a sputter coater.

Solid-state $^{13}$C NMR spectra were obtained at 75.41 MHz on a Bruker MSL 300 NMR spectrometer. The magic-angle sample spinning was maintained at about 4.0 kHz. The NMR spectra consisted of between 20,000 and 50,000 acquisitions with a contact time of 3 ms and a pulse repetition time of 4.0 ms. The chemical shifts were referenced to liquid Me$_4$Si (TMS). The NMR spectra were divide into five chemical shift regions according to the chemical types of carbon as follows 0-46 ppm (alkyl carbon), 46-110 ppm (O-alkyl carbon), 110-164 ppm (aromatic carbon) and 164-190 ppm (carbonyl carbon) (Baldock and Preston, 1995).

**Data Analysis**

The data for 1997 and 1998 were combined even through the amount of the soil in the different soil aggregate fractions was slightly higher in 1998, but not significantly different when was compared with 1997. All variables were subjected to one-way analysis of variance for each vegetation type to test for differences between treatments within an aggregate size or
organic matter fraction (SAS Institute, 1985). Where significant treatments were observed
(P=0.05), contrast analyses were performed to permit separation of means.

The soil aggregate dynamics model is a conceptual model of soil aggregate dynamics that
integrates aggregation, disruption, stabilization and destabilization processes of soil
aggregates in a framework that permits studying soil aggregate dynamics over time or
comparing ecosystems such as aggrading, degrading or steady-state systems. The soil
aggregate dynamics model is based on aggregate resistance to slaking and it assesses
aggregate dynamics through the use of the aggregate size-stability distributions of a reference
ecosystem and the new or actual size-stability distribution that result after natural or human
perturbations (Marquez, 2001). Therefore soil aggregate dynamics are probed in terms of the
processes that should take place in order to bring the system from a reference or initial state
to a final or new state see Figure 1. Values in the aggregate size-stability distribution that are
associated with the reference state are identified using the subscript \( n \) and values associated
with the new state will be referenced using the subscript \( n + 1 \).

The soil aggregate dynamics model assumes three major process: (i) the total amount of
unstable macroaggregates (> 250 µm) associated with the reference state is disrupted by a
major perturbation such as slaking, (ii) aggregate constituent units that result from the
disruption and stable aggregates from the reference state are allocated to size fractions
belonging to the new state, and (iii) the net change, in the amount of aggregates in each size
fraction, that should occur in order to bring the system to the final state is calculated and
interpreted in terms of allocation rules based on three basic processes underlying the
dynamics of soil aggregates: (i) disruption, (ii) stabilization and destabilization, and (iii)
aggregation. Although we present all the equations and definitions involved in this particular
study, the reader should bear in mind that the required equations could change depending on the particular scenario. Figure 1 shows the dynamic pathways for soil aggregates. Intrinsic model variables are shown in Table 1 and soil aggregate dynamic indices are shown in Table 2. The soil aggregate dynamics model can also be extended to the analysis of carbon associated with soil aggregates. Therefore, we use the label C-SAD (Figure 2) to emphasize that we are studying carbon associated with soil aggregate dynamics using the soil aggregate dynamics model. Intrinsic model variables are given in Table 3 and convenient indices are given in Table 4.

RESULTS

Size-Stability Distribution

Table 5 shows the amount of soil aggregates in each fraction after the slaked and capillary-wetted pretreatment as well as the respective aggregate size-stability distributions. Values in Table 5 are expressed as percentage of soil aggregate in each fraction after sand correction. The size-stability distributions show significantly higher amount of soil present as stable macroaggregates (>250 μm) under cool-season grass (53%) than under cropped system (26 %). Also, Table 5 shows that the amount of soil aggregates present as unstable macroaggregates (>250 μm) is higher under cropped system (43%) than under cool-season grass (31%). In addition, silt+clay (< 53μm) is significantly higher under cropped system (16%) than under cool-season grass (6%).
Soil Aggregate Dynamics

Disruption, stabilization/destabilization, and aggregation are the three processes underlying soil aggregate dynamics, which are assessed using the soil aggregate dynamics model.

*Disruption*—The first process underlying aggregate dynamics is disruption. Unstable macroaggregates (> 250 μm) break down in water to smaller aggregate size because the bonds are not strong enough to hold the macroaggregates together. Calculations using the soil aggregate dynamics models analytical framework indicate that when unstable large macroaggregates (>2000 μm) (U₁ = 21.6) from cool-season grass are subjected to disruptive forces 81% (G₂ = 17.5) of the material that is released is allocated to small macroaggregates of 250-2000 μm dimensions. Disruptions of unstable small macroaggregates (U₂ = 9.1) from cool-season grass are allocated to microaggregates F3 (53-250 μm) and mineral fraction F4 (<53 μm) (Figure 3).

*Stabilization/destabilization*—The second process underlying soil aggregate dynamics is stabilization and destabilization of stable macroaggregates. Figure 3 shows that only 16% (a₁ = 4.0) of the stable large macroaggregates remain from the reference state cool-season grass to the new state cropped system as stable large macroaggregate and 78% (b₁ = 20.5) of the stable large macroaggregates are destabilized and become unstable (Equation in Table 1). In addition, 84% (a₂ = 22.3) of the stable small macroaggregates remain as stable small macroaggregates and only 22% (b₂ = 6.2) are destabilized and become unstable small macroaggregates after conversion of cool-season grass to cropped system (Equation in Table
1. Microaggregates and mineral fraction, which are by definition, stable, remain in the same fraction as stable aggregates \( a_3 = 10 \) and \( a_4 = 6.3 \)

*Aggregation*—The third process underlying soil aggregate dynamics is aggregation. To assess aggregation the soil aggregate dynamics model uses net-flux (NF). The net-flux is a number that can be positive or negative; positive values are interpreted as new aggregates coming into and negative values as aggregates going out of a fraction. Aggregates can come into a fraction as a result of the aggregation of smaller aggregates or the disruption of larger aggregates (Figure 1). Similarly, aggregates can go out of a fraction by aggregation and formation of new larger aggregates or alternatively by the disruption and formation of smaller aggregates. Figure 3 shows that the net flux of large macroaggregates (> 2000 μm) is positive \( NF_1 = 8.8 \), which result in formation of new stable large macroaggregates \( x_1 \) and unstable large macroaggregates \( y_1 \). The newly formed large macroaggregates consist of only unstable large macroaggregates \( y_1 = 8.8 \) and none have been stabilized \( x_1 = 0 \). In addition, \( NF_2 \) is negative \( NF_2 = -9.5 \), the \( NF_2 \) is quantified through \( x_2 \) and \( y_2 \), which are expressed as the addition of two terms; one term accounts for the contribution from the \( G_2 \) and the other from \( NF_2 \). Thus \( x_2 = x_{2G} + x_{2NF} \) and \( y_2 = y_{2G} + y_{2NF} \), see Figure 1 and Table 1. In these equations \( x_{2G} \) is the amount of stable small macroaggregates (250–2000 μm) that result from disruption of unstable large macroaggregates (> 2000 μm). Similarly \( y_{2G} \) is the amount of unstable small macroaggregates that result from disruption of unstable large macroaggregates thus, \( G_2 = x_{2G} + y_{2G} \). Also \( x_{2, NF} \) and \( y_{2, NF} \) are the amount of stable and unstable macroaggregates that provide the net flux \( NF_2 \), thus, \( NF_2 = x_{2NF} + y_{2NF} \). Disruption
of the unstable large macroaggregates resulted in a total gain ($G_{2,n} = 17.5$) of small macroaggregates, which are allocated to $F_2$ (250-2000 µm) in cropped system; however, none of these are stable small macroaggregates ($x_{2G} = 0$), but rather unstable small macroaggregates $y_{2G} = 17.5$. Figure 3 and Table 1 show that $x_{2, NF} = 0$ and $y_{2, NF} = -9.5$ are the amounts of stable and unstable macroaggregates that provide the net flux $NF$, ($NF = -9.5$). The $NF_3 = S_{3,n+1} - (S_{3,n} + G_{3,n})$ ($NF_3 = -3.6$) and that $NF_4 = S_{4,n+1} - (S_{4,n} + G_{4,n})$ ($NF_4 = 4.3$). Therefore, the total dynamics show that $-5.1\%$ of the total $-9.5\%$ ($NF_2$) combine with microaggregates ($NF_3 = -3.6$) to form unstable large macroaggregates. This interpretation is consistent with the positive net flux in fraction one ($NF_1 = 8.8$). In addition, the results show that some of the unstable small macroaggregates ($-4.4$) of the $-9.5$ have been disrupted and released and as a consequence increase the amount of the mineral fraction that is reflected in a positive input in $F_4$ ($NF_4 = 4.3$).

**Monitoring Aggregates Dynamics**

The soil aggregates dynamics model uses some indicators to assess and monitor soil aggregate dynamics:

*Disruption index* ($DI$) is the relative amount of unstable macroaggregates > 250 µm with respect to the total amount of soil aggregates in the reference state cool-season grass (Table 2). The DI increases when the long establish cool-season grass filter ($DI_{CSG} = 31$) is converted to cropped system ($DI_{ARC} = 44$). This result indicates that under the cropped system the amount of unstable large macroaggregates that can be subjected to disruption increases 13% compared with cool-season grass (Table 7).
The formation indices (FIS and FIU): After the perturbation that produces maximum disruption in the cool-season grass system, the new cropped system restores new equilibrium conditions. The formation index quantifies the amount of stable and unstable aggregates that result directly from positive net flux (Equation in Table 2). The results in Table 7 indicate \((FIS_1)\) and \((FIS_2)\) equal to zero, that there is no formation of stable macroaggregates (> 250 \(\mu m\)) in the new-cropped system. In contrast, the predominant process was the formation of unstable macroaggregates (> 250 \(\mu m\)). \(FIU_1\) and \(FIU_2\) are equal to one (Table 7).

Stabilization and Destabilization indices (SSM and DSM): The soil aggregate dynamics model uses the stabilization of stable macroaggregates and destabilization of stable macroaggregates indices to monitor macroaggregate dynamics (Table 2). The results shown in Table 7 show that stable large macroaggregates (> 2000 \(\mu m\)) are very susceptible to becoming unstable, in fact, 84% have been destabilized \((DSM_1 = 0.84)\) and only 16% remain as stable large macroaggregates \((SSM_1 = 0.16)\) in the same fraction, following perturbation, whereas stable small macroaggregates are more stable when compared with large macroaggregates. The \(DSM_2 = 0.22\) indicates that only 22% of the stable small macroaggregates became unstable and 78% remained as stable small macroaggregates \((SSM_2 = 0.78)\) after conversion of the cool-season grass to cropped system.

Aggregation-Disruption Index (ADI): The soil aggregate dynamics model uses the aggregation-disruption index \((ADI)\), shown in Table 2, to evaluate qualitatively and quantitatively the dynamics that lead to the new state of the ecosystem after conversion from cool-season grass to cropped system. From our analysis the aggregation-disruption index is equal to \((ADI = -0.19)\), this result suggests that disruption of aggregates is the dominant process following the conversion of cool-season grass to cropped system (Table 7).
**Associated Carbon to Soil Aggregates**

Table 6 shows the measured amount of C associated with each size fraction. The results show that the amount of organic C associated with stable aggregates is 1.93 times higher under cool-season grass (23.9 mg C g\(^{-1}\)) than in cropped system (12.4 mg C g\(^{-1}\)). The amount of organic C associated with unstable aggregates in CSG (9.1 mg C g\(^{-1}\)) is not significantly different from the amount in the cropped system (9.4 mg C g\(^{-1}\)). For F4 (< 53 μm) aggregates, total organic C amounts are consistently higher in cropped system (2.4 mg C g\(^{-1}\)) than in cool-season grass (1.0 mg C g\(^{-1}\)).

**Aggregate Carbon Concentrations**

The concentration of sand-free C is strongly affected by the vegetation type and by the aggregate size class, values inside parenthesis in Figure 4. In soils under cool-season grass, sand-free C is significantly higher in stable (1.36 times) and unstable large macroaggregates (1.34 times) than in the stable and unstable large macroaggregates under cropped system. The same trend was observed in the sand-free C in the stable and unstable small macroaggregates, which are 1.42 and 1.23 times significantly greater, respectively. The concentration of sand-free C in the microaggregates under cool-season grass is 1.21 times greater than in cropped system. The concentration of sand-free C in mineral fraction (< 53 μm) under cool-season grass was not significantly different than cropped system.

**Associated Carbon to Soil Aggregate Dynamics**

The study of carbon associated with soil aggregate dynamics is based on the three basic processes considered in the soil aggregate dynamics model (Marquez, 2001). In this specific
case, the conceptualization of the soil aggregate dynamics model is done in terms of the amount of carbon associated with each aggregate size fraction (milligrams per gram whole soil) (Figure 2). We use the label C-soil aggregate dynamics to emphasize that we are studying carbon associated with soil aggregate dynamics using the soil aggregate dynamics model (Equations in Table 3 and results in Figure 4).

Disruption—Figure 4 shows that 6.7 mg C g⁻¹, that is associated with the unstable large macroaggregates (CUi = 6.7 mg C g⁻¹) is released when unstable large macroaggregates (> 2000 μm) break down in water to small aggregate fractions, 78% of the C, associated with this fraction, is allocated as C associated with unstable small macroaggregates and 22% is allocated as C associated with aggregates < 250 μm. The C associated with unstable small macroaggregates is completely allocated to aggregates < 250 μm after complete destruction of unstable aggregates.

Stabilization/destabilization—Figure 4 shows that 13% (Ca₁ = 1.3 mg C g⁻¹) of the C associated with stable large macroaggregates in the cool-season grass remains as C associated with stable large macroaggregates in the cropped system while 87% (Cb₁ = 8.5 mg C g⁻¹) of the C associated with stable large macroaggregates in the cool-season grass becomes associated with the unstable large macroaggregates fraction in the cropped system. Figure 4 also shows that 56% (Ca₂ = 6.0 mg C g⁻¹) of the C associated with stable small macroaggregates in the cool-season grass remains as C associated with stable small macroaggregates in the cropped system and 44% (Cb₂ = 4.7 mg C g⁻¹) of the C associated with stable small macroaggregates in the cool-season grass becomes associated with the unstable small macroaggregates in the cropped system.
Aggregation—The net-flux in F1 \((CNF_1 = -2.0 \text{ mg C g}^{-1})\), F2 \((CNF_2 = -7.9 \text{ mg C g}^{-1})\) and F3 \((CNF_3 = -1.8 \text{ mg C g}^{-1})\) indicates loss of soil organic carbon (Figure 4, equations in Table 3). This is carbon that has been protected in the cool-season grass but has become relatively labile to decomposers as a consequence of the destabilization of macroaggregates in the cropped system. Also carbon that was associated with the small macroaggregate size can be released and lost by surface erosion.

Monitoring Carbon Associated with Soil Aggregates Dynamics

The soil aggregate dynamics model uses several indicators to assess and monitor associated carbon with aggregate dynamics (Equations in Table 4).

Associated Carbon Disruption \((CD)\)—is the amount of carbon associated with unstable macroaggregates (>250 \(\mu\)m). Table 8 shows that \(CD_{CSG} = 9.10 \text{ mg C g}^{-1}\) for the reference state ecosystem cool-season grass and \(CD_{ARC} = 9.40 \text{ mg C g}^{-1}\) for the newly established cropped system.

Associated Carbon to Formation of Stable \((CFIS)\) and to Formation of Unstable \((CFIU)\)—are defined as the amount of associated carbon with formation of stable macroaggregates \((CFIS)\) and the amount of carbon associated with formation of unstable macroaggregates \((CFIU)\). Table 8 shows that \(CFIS = 0\) and \(CFIU = 0\) which indicates that there is no new carbon physically protected or temporarily sequestered as a result of the formation of new macroaggregates (> 250 \(\mu\)m) when the cool-season grass is replaced by the cropped system.
Carbon Associated with Stabilization (CSSM) and Destabilization (CDSM)—these indicators are used to quantify the amount of carbon associated with stabilization (CSSM) and destabilization (CDSM) of stable macroaggregates after conversion of the CSG to ARC. Table 8 shows that $CDSM_1 = 0.87$ and $CSSM_1 = 0.13$. This is interpreted as 86% of the carbon that was associated with the stable large macroaggregates in the cool-season grass is now associated with unstable large macroaggregates in the cropped system and only 13% of this carbon remains associated with the stable large macroaggregates in the cropped system during the conversion of the long establish cool-season grass to cropped system. In addition Table 8 shows that $CDSM_2 = 0.44$ and $CSSM_2 = 0.56$ therefore 44% of the carbon that was associated with stable small macroaggregates in the cool-season grass is now associated with unstable small macroaggregates in the cropped system and the rest, 56%, remains as C associated with stable small macroaggregates.

Carbon Associated with Aggregation and Disruption (CAD)—Results indicated that $CAD = -11.30$ mg C g$^{-1}$ of the carbon associated with aggregates is lost as a consequence of the break up of macroaggregates after conversion of the cool-season grass to cropped system (Table 8).

Organic Carbon Fractions

Total soil organic C in the cool-season grass plots is significantly higher (31 mg C g$^{-1}$) than (21 mg C g$^{-1}$) under cropped system (Figure 5). The mineral-associated carbon (FMC) content has the same pattern as the total soil organic carbon (TOC) in the whole soil (Figure 6). When averaged across one year (1997-1998), significant differences in total particulate
organic matter (TPOM-C = LPOM-C + HPOM-C) content, are observed between cool-season grass (4.95 mg C g\(^{-1}\)) and cropped system (1.66 mg C g\(^{-1}\)) (Figure 6). The amount of TPOM-C under the cool-season grass accounted for 16% of the total organic C but only 8% under cropped system. The LPOM-C and the HPOM-C was higher under cool-season grass than cropped system. The amount of LPOM-C under cool-season grass and cropped system accounted for 81% and 19% of the HPOM-C of the TPOM-C, respectively (Figure 6).

**Chemical Composition of Light Particulate Organic Matter**

The relative proportions of the NMR spectra of different types of carbon in LPOM-C at a depth of 0–15 cm under cool season grass filter and non-buffered annual row cropped field are shown in Figure 7. The major signal for the L-POM (<1.85 g cm\(^{-3}\)) obtained by the fractionation procedures describes above was from the 46-110 ppm region (O-alkyl C) with peaks at 74 ppm, indicating that the carbohydrates are quantitatively the most significant compounds in this fraction. Carbohydrates comprise 50-70% of the dry weight of most plant tissue, and hence are the most abundant materials added to soil in the form of plant residue. The O-alkyl accounted for 52 and 59% under cropped system during July and November respectively. Following the pattern the O-alkyl accounted 49-57% under CSG during July and November respectively. The contribution of alkyl and aromatics C were much smaller (13-29%) except, that the amount of alkyl C that accounted for 46% during July 97 under cropped system. The carbonyl C occurred in the lowest quantities (7-11%). This confirms the hypothesis that the LPOM-C is a fraction that is composed by partially decomposed organic matter. The ratio of O-alkyl to alkyl C has been used to understand decomposition process. The ratio O-alkyl to alkyl C was lower in July and increase in November under
cool-season grass, the lower ratio during July is associated with a higher decomposition rate which is to associate the loss of the most easily metabolized carbohydrates and accumulation of alky C (Preston, 1996). The same pattern was observed under cropped system, the decomposition was higher in July compared with November. The results indicate a faster decomposition of O-alkyl C in the cropped soils compared with the cool-season grass, in addition the results show that the decomposition is faster in July. The rapid decomposition of carbohydrates rich POM is retarded when it is coated within mineral particles (Golchin et al, 1998). Polysaccharides are thought to be transitory binding agents (Tisdall and Oades, 1982) since microorganism can rapidly metabolize them. If their role in aggregate stabilization is more than transitory then they must be continually replenished and/or become physically or chemically protected from microbial decomposition in some way.

Microscopic Observations of Aggregates

Figure 8 clearly shows evidence that under cool-season grass, root and fungal hyphae form an extensive network around the large macroaggregates (> 2000μm) which entangle particles and microaggregates into macroaggregates, that are then stabilized. In contrast, Figure 9 shows evidence that under cropped system there is no presence of fine roots and fungal hyphae and the POM is less homogeneously distributed among the soil particles. In addition, Figure 10 and Figure 11 provide evidence that reinforce the conclusion that clay content plays an important role in maintaining stables small macroaggregates under both cool-season grass and cropped system. Figure 12 shows the different degrees of destabilization that occur between July to November under cool-season grass and under
cropped system. Large macroaggregates are bigger in size and do not show failure planes under cool-season grass in contrast aggregates takes during November shows fractures together with different levels of root and hyphae decomposition. Another important point is that roots in different states of decomposition bound stable large and small macroaggregates.

DISCUSSION

A long established riparian cool-season grass filter ecosystem is used as a reference state and a non-buffered annual row cropped system as a new state to study soil degrading process following the conversion of cool-season grass filter to non-buffered cropped system. The results indicate that the amounts of unstable macroaggregates increase significant as a consequence of the establishment of cropped system; the ratio between stable large macroaggregates to unstable large macroaggregates (SLM/ULM) is 1.13 under CSG and 0.14 under ARC. Is clear that the lack of perturbation under perennial grass favors the formation and stabilization of large macroaggregates. In contrast, under cropped system tillage shortens the lifetime of macroaggregates by increasing soil aggregate break down. This in turns accelerates OM decomposition due to reduced physical protection and reduces the formation rate of new macroaggregates.

The susceptibility of destabilization of the large stable macroaggregates under cool-season grass occurs because the binding agents that maintain stable large macroaggregates consist mainly of temporary and transient organic materials such as fine roots and fungal hyphae, LPOM and HPOM. Electronic micrographs clearly showed evidence that under cool-season grass roots and fungal hyphae form an extensive network around the large macroaggregates (> 2000 μm), and thus maintain the stability of the macroaggregates. The
network of encrusted roots and hyphae hold the macroaggregates intact, hence they do not collapse in water. Similarly, Elliot and Coleman (1998) suggest that roots and fungal hyphae entangled microaggregates to form macroaggregates, which are then stabilized by extracellular polysaccharides. Chenu (1989) suggested that the fungi reorganize clay particles into aggregates and then stabilize these aggregates with extracellular polysaccharides. In contrast, under cropped system continuous cultivation breaks the network of roots and hyphae, SEM photos shows no presence of fine roots and fungal hyphae and the POM is less homogeneously distributed among the soil particles so that macroaggregates are readily destabilized, this makes macroaggregates under cropped system more susceptible to collapse in water.

Stable large macroaggregates have significantly higher organic matter concentrations under CSG than under ARC (Figure 4). Cover year round by (C3) grasses, is reflected in continuous inputs of organic matter, promotes the stabilization of both large and small macroaggregates and the accumulation of carbon with at higher concentration than under cropped system (Figure 4).

The turnover of large macroaggregates in cool-season grass with dimension between 6-8 mm is a transient process that depends on growing and subsequent fragmentation and decomposition of fine roots, very fine roots, and hyphae. As a result of decomposition of the organic matter large macroaggregates with dimensions of 6-8 mm are susceptible to fail and to be disrupted. The result of the destabilization and disruption of large macroaggregates with dimension between 6-8 mm is stable large macroaggregates with dimensions between 2-4 mm (Figure 12).
Soils under cool-season grass receive continuous inputs of organic matter that controls the stabilization/destabilization rate of macroaggregates. The stability of a portion of macroaggregates decreases due to the decomposition processes, other macroaggregates are simultaneously being formed and stabilized. This is reflected in the ratio between stable large macroaggregates to unstable large macroaggregates ~1.13 under CSG and, in reality the stabilization of new macroaggregates may occur at the expense of the breakdown of older less stable macroaggregates. This is confirmed with the lower C concentration in the unstable and small macroaggregates, such as was reported by Puget et al., (1995), Golchin et al., (1994), and Gale et al., (2000), who reported that the stable macroaggregates are richer in total and in young C than the unstable ones.

The ratio of stable small macroaggregates/unstable small macroaggregates increases in both systems with respect to the ratio for large macroaggregates, however the ratio between stable small macroaggregates to unstable small macroaggregates (SSM/USM) is 3.03 under cool-season grass and 1.57 under cropped system. These values indicate that there are more stable small macroaggregates than unstable small macroaggregates. The greater stability of small macroaggregates compared with large macroaggregates is associated with the fact that the binding agents that maintain stable small macroaggregates are more related with clay binding agents and not with organic materials such as fine roots and fungal hyphae. The soil aggregates dynamics model indicates that 78% of the stable small macroaggregates under cool-season grass remain as stable small macroaggregates under cropped system and they are not destabilized as a consequence of field perturbations upon converting cool-season grass to cropped system.
Electronic micrographs of small macroaggregates under cool-season grass (Figure 10) show that there is no root or hyphae network to hold the small macroaggregates together. This result suggests that the stability of small macroaggregates depends on a complex of clay and organic matter. Chenu and Guérif (1991) and Chenu (1993) found that clay-polysaccharide associations increase the strength of aggregates through the formation of polymeric bridges between clay particles and the coverage of the surface area of the clay.

The lower value of the destabilization index ($DSM_2 = 0.22$) results from the great stability of small macroaggregates under cool-season grass. In turn, this index indicates that after conversion of cool-season grass to cropped system only 22% of the stable small macroaggregates have been destabilized. However, the carbon concentration of stable small macroaggregates under cropped system is lower than the C concentration of stable small macroaggregates under cool-season grass. One of the reasons for this difference in C concentration is that under cool-season grass the formation of stable small macroaggregates is a continuous process sustained by the continuous provision of new and young OM with a higher C concentration. In contrast, the lower C concentration of stable small macroaggregates under cropped system suggests that important amounts of stable small macroaggregates under cropped system are old stable small macroaggregates that remain from the cool-season grass. In our samples the NMR analysis showed that the chemical composition of the LPOM was mainly O-alkyl C (polysaccharides) with a maximum at 74 ppm. Although the chemical composition of both samples is similar, the amount of LPOM under cool-season grass is 2.8 times greater than under cropped system. Another reason is that an increase in alkyl between November to July under cropped system suggests that LPOM is mineralized at faster rates than under cool-season grass, as a consequence the role
of stabilization of this polysaccharide is limited. In contrast under cool-season grass the mineralized LPOM occurs at a rate that the polysaccharides is more than a transitory binding agent and become physically protected by microbial decomposition because they are continually replenished under cool-season grass. Thus, there is a continuous rejuvenator of the organic matter that maintains the organic C concentration higher than under cropped system. Cultivation inhibits the formation of new small macroaggregates and increases decomposition due to reduced physical protection.

On the other hand, SEM micrographs show that the small macroaggregates under the cropped system are not as angular. They have more round features and have random POM associated with them that is not well incorporated in them. These features reflect the aboveground crop debris is frequently mixed into the surface plow layer at the end of the growing season.

The conversion of establish cool-season grass buffers to annual row crop production, as well as disrupting macroaggregates and promoting organic matter oxidation, also resulted in a marked reduction in the input of organic material to the soil particularly in the form of plant roots. The ADI value and sign suggest that the “net” effect after the conversion of cool-season grass to cropped system is disruption of 19% of the soil aggregates under cool-season grass, which in turn shifts the size distribution to smaller sizes fractions.

The conversion of cool-season grass to cropped system favors the breakdown and destabilization of stable macroaggregates and produce the loss of 11.3 mg C g⁻¹ through three possible mechanisms: (i) previously physically-protected organic matter gets greater exposure to soil micro-organisms, thus particulate organic matter, which is comprised primarily of partially decomposed root segments, can account for a significant portion of
organic matter that is initially loosed from macroaggregates as result of cultivation (Cambardella and Elliot 1992); (ii) reduction in the amount of C as a result of erosion due to the loss of top soil and to a dilution effect from subsoil mixing following cultivation (Paustian et al., 1997), and (iii) leaching.

Physical fractionation of soil organic matter confirms that cultivation results in the loss of 10 mg C g\(^{-1}\) of total TOC when cool-season grass was converted in cropped system. TPOM-C represents 3.29 mg C g\(^{-1}\) of these 10 mg C g\(^{-1}\) and the rest, 6.71 mg C g\(^{-1}\) are associated with the mineral fraction. This result is in agreement with the total loss of C calculated using the soil aggregates model model. The break down of stable macroaggregates promotes decomposition of 3.29 mg C g\(^{-1}\) and the loss of 6.71 mg C g\(^{-1}\) of carbon associated with microaggregates and mineral particles (silt+clay). This carbon is released as a result of the disruption of macroaggregates; as a consequence these small aggregate sizes are more susceptible to be lost by erosion.

It is well known that plant communities that include species with extensive root systems (Cool season grass (C3)) can produce the highest levels of macroaggregation. Hetrick et al., (1998) found that cool-season C3 grasses have finer root systems and more primary and secondary roots than warm season grasses and the diameter of the primary, secondary, and tertiary roots of the cool season grasses are significantly smaller than those of warm-season grasses. Haynes (2000) showed the positive effect that a short term (5-yr) pasture with C3 grasses provides more soil organic matter and increased aggregate stability than adjacent cropped soils. Studies conducted by Tufekcioglu et al (1999) in the same research area as this study, reported that cool season grass had significantly dead fine root biomass (2255 kg ha\(^{-1}\)) than either maize or soybean crops (645 or 653 kg ha\(^{-1}\)). In addition, Pickle (1999)
found on the same sites, that cool season grass consistently had the higher amounts of microbial biomass (327 mg C kg soil$^{-1}$) than crops (100 mg C soil$^{-1}$). These results suggest that aggregate formation and stabilization under cool-season grass is relate to: (i) fine roots, (ii) more deadd roots, (iii) higher biomass- C, (iv) moderate rates of mineralization, (v) low O-alky/alkyl ratio, (v) high inputs of light and heavy particulate organic matter and, (vi) presence of fungal hyphae. All of these factors together indicate that cool-season grasses favor the formation and stabilization of stable macroaggregates and carbon sequestration under riparian soils.

Under cropped system aggregates disruption exposes POM that has been protected but relatively labile to decomposers, resulting in a loss of 11.3 mg C g$^{-1}$ of SOM and further destabilization of 84% of stable large macroaggregates and 22% of the small macroaggregates. These processes inhibit the establishment of dynamic pathways (Marquez, 2001) associated with the formation of stable large and small macroaggregates and promote processes related with microaggregates that are in turn more stable to be disrupted.

**CONCLUSIONS**

Surface soils under cool-season grass have significantly higher percentage of soil aggregates present as stable macroaggregates (53%) compared (26 %) under surface soils under cropped system. Conversion of cool-season grass to cropped system results predominantly in the formation of unstable macroaggregates (>250 μm). The results also showed that stable large macroaggregates are very susceptible to be destabilized, in fact 84% have destabilized and only 16% remained as stable large macroaggregates in the same fraction. Small macroaggregates are more stable when compared with large macroaggregates.
Calculation indicates that only 22% of them became unstable and 78% remain as stable small macroaggregates after conversion of the cool-season grass to annual cropped system.

In overall the “net” dominant process that leads the new state after conversion of cool-season grass to cropped system was disruption. The results indicate that 11.30 mg C g$^{-1}$ of the carbon associated with macroaggregates was lost as a consequence of the break down of aggregates after introversion of the cool-season grass. Although the chemical composition of both samples is similar the amount of LPOM under cool-season grass is 2.8 times greater than under cropped system. The higher increase in alkyl between November to July under cropped system suggests that LPOM is mineralized at rates faster than under cool-season grass, as a consequence the role of stabilization of this polysaccharide is limited. In contrast under cool-season grass the mineralization LPOM occurs at a rate where polysaccharides is more than transitory binding agents and become physically protected by microbial decomposition because they are continually replenished under cool-season grass. Thus, there is a continuous rejuvenation of the organic matter that maintains a higher organic C concentration under cool-season grass than under cropped system.

Preservation of established riparian cool-season grass filters is an important alternative to maintain the functioning of soil. In fact, cool-season grass plays an important role in the formation and stabilization of aggregates, which in turn has protected and temporary sequestered 11.3 mg C g$^{-1}$. It is important, to supply nutrients, store water, release greenhouse gases, modify pollutants, resist physical degradation and maintain sustainable ecosystem.
REFERENCES


Figure 1. Dynamic pathways for soil aggregates using the soil aggregate dynamics (SAD) model (Marquez, 2001). $S = \text{stable aggregates}$, $U = \text{unstable aggregates}$, $NF = \text{net flux}$, $G = \text{gains}$, $x = \text{new stable macroaggregates when } NF > 0$, $y = \text{new unstable macroaggregates when } NF > 0$, $a = \text{stable macroaggregates that remain stable}$, and $b = \text{stable macroaggregates that become unstable}$, $n = \text{reference state}$, and $n+1 = \text{new state}$.
Figure 2. Carbon associated with aggregate dynamics pathways. $CS =$ carbon associated with stable aggregates, $CU =$ carbon associated with unstable aggregates, $CNF =$ carbon associated with net flux, $CG =$ carbon associated with gains, $Cx =$ carbon associated with new stable macroaggregates, $Cy =$ carbon associated with new unstable macroaggregates, $Ca =$ carbon associated with stable macroaggregates that remain stable, and $Cb =$ carbon associated with stable macroaggregates that become unstable, $n =$ reference state, and $n+1 =$ new state.
Figure 3. Dynamic pathways of aggregates using the riparian cool season grass filter as a steady state condition and non-buffered annual row cropped system as a degrading system. Values are on pooled data from 1997 and 1998 expressed on sand-free basis as % of soil aggregates ± 0.1 in each size fraction. \( S \) = stable aggregates, \( U \) = unstable aggregates, \( NF \) = net flux, \( G \) = gains, \( x \) = new stable macroaggregates when \( NF > 0 \), \( y \) = new unstable macroaggregates when \( NF > 0 \), \( a \) = stable macroaggregates that remain stable, and \( b \) = stable macroaggregates that become unstable.
Figure 4. Dynamic of soil organic carbon associated with aggregates at a depth of 0-15 cm in riparian cool season grass filters (CSG) and non-buffered annual row crops (ARC). Values are on pooled data from 1997 and 1998 expressed in mg C g\(^{-1}\) (± 0.1). Values inside of parenthesis are aggregate carbon concentration expressed mg C g\(^{-1}\) sand-free aggregates. \(CS\) = carbon associated with stable aggregates, \(CU\) = carbon associated with unstable aggregates, \(CNF\) = carbon associated with net flux, \(CG\) = carbon associated with gains, \(Cx\) = carbon associated with new stable macroaggregates, \(Cy\) = carbon associated with new unstable macroaggregates, \(Ca\) = carbon associated with stable macroaggregates that remain stable, and \(Cb\) = carbon associated with stable macroaggregates that become unstable.
Figure 5. Total soil organic carbon (TOC) and mineral fraction associated carbon (FMC) at a depth of 0-15 cm under riparian cool-season grass filter (CSG) and non-buffered annual row cropped (ARC). Different letters indicate differences ($P<0.05$) between vegetation treatments within size class.
Figure 6. Total particulate organic matter carbon (TPOM-C), light particulate organic matter carbon (LPOM-C) and heavy particulate organic matter carbon (HPOM-C) at a depth of 0 – 15 cm under a cool season filter (CSG) and non-buffered annual row cropped field (ARC). Different letters indicate differences (P<0.05) between vegetation treatments within a size class.
Figure 7. The relative proportions of different types of carbon in LPOM-C at a depth of 0 – 15 cm under a cool season filter (CSG) and non-buffered annual row cropped field (ARC).
Figure 8. Macroaggregates > 2000 µm from a fine loamy soil from under a long established riparian cool-season grass filter along Bear Creek in central Iowa, (a) macroaggregates composed of many microaggregates bound with fine roots. (b) Close up of macroaggregates bound together mainly by an enmeshing network of fungal hyphae and roots. (c, d, e, f) Close up of hyphae of the root-associated fungus interconnecting particles.
Figure 9. Macroaggregates > 2000 μm in a fine loamy under annual row cropped riparian soils from Bear Creek Iowa, (a, b) macroaggregates > 2000 μm showing sand particles encrusted with an agglomeration of smaller macroaggregates and microaggregates. (c, d, e, f) Close up of plants fragments associated with inorganic soil particles in a fine loamy soil under annual row cropped riparian soils along Bear Creek Iowa.
Figure 10. Small macroaggregates (250 – 2000 μm) under a long established riparian cool-season grass filter along Bear Creek in Central Iowa.
Figure 11. Small macroaggregates (250 - 2000 μm) under annual row cropped riparian soils along Bear Creek in Central Iowa.
Figure 12. Different degrees of decomposition of macroaggregates from a fine loamy soil from a long established riparian cool-season grass filter (right side) and from under annual row cropped (left side) riparian soils from Bear Creek Iowa.
Table 1. Summary of intrinsic variables involved in the soil aggregates model. The reader should be aware that some of the equations could change if the scenario is different. \( S \) = stable aggregates, \( U \) = unstable aggregates, \( NF \) = net flux, \( G \) = gains, \( x \) = new stable macroaggregates when \( NF > 0 \), \( y \) = new unstable macroaggregates when \( NF > 0 \), \( b \) = stable macroaggregates that become unstable, \( T \) is total percentage of soil aggregates, \( n \) = reference state, and \( n+1 \) = new state.

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Table 2. Summary of indices used by the soil aggregates model to assess soil aggregate dynamics. The reader should be aware that some of the equations could change if the scenario is different. FIS = formation index of stable macroaggregates. FIU = formation index of unstable macroaggregates. DSM = index of destabilization of macroaggregates. SSM = Stabilization of stable macroaggregates. $x_2$ = net-change of stable macroaggregates. $y_2$ = net-change of unstable macroaggregates. DI = disruption index. A = represents the amount of aggregates that result for aggregation. d = disruption. ADI = aggregation-disruption index.

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Table 3. Summary of intrinsic variables involved in the soil aggregate dynamics model studying the associate carbon. The reader should be aware that some of the equations could change if the scenario is different. $CS = \text{carbon associated with stable aggregates}$, $CU = \text{carbon associated with unstable aggregates}$, $CNF = \text{carbon associated with net flux}$, $CG = \text{carbon associated with gains}$, $Cx = \text{carbon associated with new stable macroaggregates}$, $Cy = \text{carbon associated with new unstable macroaggregates}$, $Ca = \text{carbon associated with stable macroaggregates that remain stable}$, and $Cb = \text{carbon associated with stable macroaggregates that become unstable}$, $TCNF = \text{total C associated with net flux}$, $n = \text{reference state}$, and $n+1 = \text{new state}$.

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Table 4. Summary of indicators and indices used by the SAD model to assess associated carbon to soil aggregate dynamics. The reader should be aware that some of the equations could change if the scenario is different. CD = carbon associated with unstable macroaggregates. CFIS = associated Carbon to formation of stable, and CFIU = associated carbon to formation of unstable, CSSM = carbon Associated with Stabilization, and CDSM = carbon associated with destabilization, Cx = carbon associated with new stable macroaggregates, Cy = carbon associated with new unstable macroaggregates, CAD = carbon associated with aggregation and disruption, CS = carbon associated with stable aggregates, CU = carbon associated with unstable aggregates, CNF = carbon associated with net flux, CG = carbon associated with gains, CX = carbon associated with new stable macroaggregates, Cy = carbon associated with new unstable macroaggregates, Ca = carbon associated with stable macroaggregates that become unstable, TCNF = total C associated with net flux. n = reference state, and n+1 = new state

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Table 5. The aggregate size-stability distribution under riparian cool season grass filters and annual row cropped systems. Values are on pooled data from 1997 and 1998 expressed on a sand-free basis as % of soil aggregates ± 0.1 in each size fraction. Different letters indicate differences (P<0.05) between vegetation treatments within size class. \( TS \) is the total percentage of stable aggregates and \( TU \) is the total percentage of unstable aggregates. \( T \) is total percentage of soil aggregates \( T = TS + TU \).

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<td>Cool season grass filter (CSG)</td>
<td></td>
</tr>
<tr>
<td>&gt; 2000</td>
<td>24.5</td>
<td>46.1</td>
</tr>
<tr>
<td>250 - 2000</td>
<td>46.0</td>
<td>37.6</td>
</tr>
<tr>
<td>53 - 250</td>
<td>17.8</td>
<td>10.0</td>
</tr>
<tr>
<td>&lt;53</td>
<td>11.7</td>
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<td>Total</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td></td>
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</tbody>
</table>

NEW STATE
Annual row cropped (ARC)

<table>
<thead>
<tr>
<th>Size fraction (( \mu m ))</th>
<th>Water pretreatments</th>
<th>Aggregate size-stability distribution (SSD)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
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<tr>
<td>&gt; 2000</td>
<td>4.0</td>
<td>33.3</td>
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<tr>
<td>250 - 2000</td>
<td>43.7</td>
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<td>53 - 250</td>
<td>24.3</td>
<td>14.2</td>
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<tr>
<td>&lt;53</td>
<td>28.0</td>
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<td>Total</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td></td>
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</tr>
</tbody>
</table>

\( TS = 69.3a \) \( TU = 30.7a \)

\( TS = 56.5b \) \( TU = 43.5b \)
Table 6. Amount of organic C associated with each aggregate size fraction. Values are on pooled data from 1997 and 1998 expressed in mg C g\(^{-1}\) (± 0.1). Different letter indicate differences (P<0.05) between vegetation treatments within size class. CTS is the amount of carbon associated with stable aggregates and CTU is the amount of carbon associated with unstable aggregates. CT is the amount of carbon associated with soil aggregates CT = CTS + CTU.

<table>
<thead>
<tr>
<th>Size fraction</th>
<th>Carbon associated with aggregates after water pretreatments</th>
<th>Carbon associated with aggregates after determination of the size-stability distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>μm</td>
<td>Slaked</td>
<td>Capillary-wetted</td>
</tr>
<tr>
<td>&gt; 2000</td>
<td>9.8</td>
<td>16.5</td>
</tr>
<tr>
<td>250 - 2000</td>
<td>16.8</td>
<td>13.1</td>
</tr>
<tr>
<td>53 - 250</td>
<td>4.5</td>
<td>2.4</td>
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<td>&lt; 53</td>
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<td>1.0</td>
</tr>
<tr>
<td>Total</td>
<td>33.1</td>
<td>33.0</td>
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</tbody>
</table>

REFERENCE STATE
Cool season grass filter (CSG)

<table>
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<tr>
<th>Size fraction</th>
<th>Carbon associated with aggregates after water pretreatments</th>
<th>Carbon associated with aggregates after determination of the size-stability distribution</th>
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</thead>
<tbody>
<tr>
<td>&gt; 2000</td>
<td>1.3</td>
<td>7.8</td>
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<tr>
<td>250 - 2000</td>
<td>10.2</td>
<td>8.9</td>
</tr>
<tr>
<td>53 - 250</td>
<td>5.3</td>
<td>2.7</td>
</tr>
<tr>
<td>&lt; 53</td>
<td>4.9</td>
<td>2.4</td>
</tr>
<tr>
<td>Total</td>
<td>21.7</td>
<td>21.8</td>
</tr>
</tbody>
</table>

NEW STATE
Annual row cropped (ARC)

<table>
<thead>
<tr>
<th>Size fraction</th>
<th>Carbon associated with aggregates after water pretreatments</th>
<th>Carbon associated with aggregates after determination of the size-stability distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 2000</td>
<td>9.8</td>
<td>16.5</td>
</tr>
<tr>
<td>250 - 2000</td>
<td>16.8</td>
<td>13.1</td>
</tr>
<tr>
<td>53 - 250</td>
<td>4.5</td>
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<td>1.0</td>
</tr>
<tr>
<td>Total</td>
<td>33.1</td>
<td>33.0</td>
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</table>
Table 7. Indicators of soil aggregate dynamics. Values are on pooled data from 1997 and 1998. FIS = formation index of stable macroaggregates. FIU = formation index of unstable macroaggregates. DSM = Index of destabilization of macroaggregates. SSM = Stabilization of stable macroaggregates. $x_2$ = net-change of stable macroaggregates. $y_2$ = net-change of unstable macroaggregates. DI = disruption index. A = represents the amount of aggregates that result for aggregation. d = disruption. ADI = aggregation-disruption index.

<table>
<thead>
<tr>
<th>Size Fraction</th>
<th>FIS</th>
<th>FIU</th>
<th>DSM</th>
<th>SSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 2000 μm</td>
<td>0.00</td>
<td>1.00</td>
<td>0.84</td>
<td>0.16</td>
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<tr>
<td>250–2000 μm</td>
<td>0.00</td>
<td>1.00</td>
<td>0.22</td>
<td>0.78</td>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>$x_2$</th>
<th>$y_2$</th>
<th>DI</th>
<th>A</th>
<th>d</th>
<th>ADI</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSG</td>
<td>31</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ARC</td>
<td>0.00</td>
<td>8.00</td>
<td>44</td>
<td>8.80</td>
<td>4.30</td>
<td>-0.19</td>
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</table>
Table 8. Indicators for carbon associated with aggregates dynamics pathways. Values are on pooled data from 1997 and 1998. CD = carbon associated with unstable macroaggregates (>250 μm). CFIS = associated Carbon to formation of stable, and CFIU = associated carbon to formation of unstable, CSSM = carbon Associated with Stabilization, and CDSM = carbon associated with destabilization, Cx = carbon associated with new stable macroaggregates, Cy = carbon associated with new unstable macroaggregates, CAD = carbon associated with aggregation and disruption.

<table>
<thead>
<tr>
<th>Size Fraction</th>
<th>CFIS</th>
<th>CFIU</th>
<th>CDSM</th>
<th>CSSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 2000 μm</td>
<td>0.00</td>
<td>0.00</td>
<td>0.87</td>
<td>0.13</td>
</tr>
<tr>
<td>250 – 2000 μm</td>
<td>0.00</td>
<td>0.00</td>
<td>0.44</td>
<td>0.56</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>*Cx₂</th>
<th>*Cy₂</th>
<th>*CD</th>
<th>*CA</th>
<th>*Cd</th>
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<tr>
<td>CSG</td>
<td>9.10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ARC</td>
<td>0.00</td>
<td>-1.80</td>
<td>9.40</td>
<td>0.00</td>
<td>0.40</td>
<td>-11.30</td>
</tr>
</tbody>
</table>

*Values expressed in mg C g⁻¹
SOIL AGGRADATION FOLLOWING CONVERSION OF AGRICULTURAL ROW CROPS TO RIPARIAN SWITCHGRASS BUFFERS

C.O. Marquez, C.A. Cambardella, R.C. Schultz, and T.M. Isenhart

ABSTRACT

In this study we use the aggregate size-stability distribution and the soil aggregate dynamics model to monitor soil aggregation in a riparian soil following conversion of agricultural row crops to switchgrass filters. Aggregate size fractions were separated by wet sieving using the aggregate size-stability protocol. The proportion of soil and total organic C was quantified for each aggregate size class. Soil organic matter fractions were isolated by size and density into light particulate organic matter, heavy particulate organic matter, total particulate organic matter and mineral fraction organic matter. The amount of stable large and small macroaggregates in the switchgrass 7 years after establishment was not significantly different than in the cropped system. However, there were significantly more unstable large and small macroaggregates under the switchgrass than under the cropped system. The soil aggregate dynamics model indicates that aggregation is the “net” process that leads to a 3% increase in new, primarily unstable, macroaggregates. Total soil organic C in the switchgrass plots was higher but not significantly different from cropped system. The amounts of total, light and heavy particulate organic matter did not differ between switchgrass and cropped system. The storage of soil organic C under switchgrass occurs at a rate of $-43 \text{ g m}^{-2} \text{ y}^{-1}$. The low rate of aggregation, soil stabilization, and soil organic C storage under switchgrass is related to: (i)
the large number of coarse roots; (ii) lower inputs of light and heavy particulate organic matter; (iii) no changes in the alkyl-C/O-alkyl-C ratio over time; and (iv) light particulate organic matter with a high C/N ratio. The perennial nature of switchgrass suggest that this native grass could have the potential to stabilize newly unstable small and large macroaggregates if the binding agents related with the inputs of organic matter increased as a consequence of an increase in the rate of residue decomposition over time. In contrast under cropped system, yearly soil perturbations inhibit the formation of new stable large and small macroaggregates. As a consequence promote the disruption of unstable large and small macroaggregates, exposing particulate organic matter that has been protected to decomposition, resulting in a loss of soil organic matter and further destabilization of stable macroaggregates. These degradable processes jeopardize the soil’s capacity to function as healthy riparian system.

INTRODUCTION

Riparian zones have important geomorphic and hydrologic roles and support high levels of biological productivity. Although riparian areas may occupy only a small area of a watershed, they represent an important component of the overall landscape (Elmore and Breschta, 1987). Healthy riparian areas stabilize stream channels, provide sediment storage, serve as nutrient sinks for the surrounding watershed and improve the quality of water leaving the watershed (DeBano and Schmidt, 1989).

Most riparian zones in agricultural and urban landscapes have long been negatively influenced by human activities. The frequent disturbance of riparian zones has a direct
influence on water quality, hydraulic alteration of waterways, reduction in soil quality, and disruption of wildlife habitats and populations (Schultz et al., 1995).

Considerable attention has recently been focused on the restoration of riparian forest and grass buffer systems. Numerous approaches have been adopted for mitigating the adverse impacts of agricultural practices within the context of a bio-assimilative strategy. These include the restoration of riparian vegetative buffers (Osborne and Kovacic, 1993). Most restoration programs include cool-season (C3) and warm-season grasses (C4) to reduce water runoff and sediment loss, and help soil development processes by improving soil organic matter, soil structure, and soil water and nutrient-holding capacity (Lowrance et al., 1984; Schultz et al., 1995; Kort et al., 1998; Corre et al., 1999). In 1990, the Agroecology Issues Team of the Leopold Center for Sustainable Agriculture at Iowa State University (ISU) established a multi-species riparian buffer along Bear Creek in central Iowa, USA. Bear Creek is typical of many streams in central Iowa where the primary land use within the watershed, including the riparian zone, is row crop agriculture (corn and soybean) or intensive grazing (Schultz et al., 1995). Four years after establishment of the multi-species riparian buffer along Bear Creek, (Schultz et al., 1995) reported dramatic alterations in the appearance and function of the riparian buffer. Specifically, the root biomass increased significantly below the multi-species riparian buffer compared with agricultural crops. In addition, nitrate-nitrogen concentrations in the multi-species riparian buffer never exceed 2 mg l⁻¹ whereas the average levels in the adjacent agricultural fields exceed 12 mg l⁻¹. These results support the idea that the new aggrading conditions are leading to the restoration of the multi-species riparian buffer along Bear Creek.
In aggrading systems, organic inputs lead to the formation and stabilization of aggregates, which in turn can protect soil organic matter from decomposition, leading to further aggregate stabilization (Jastrow and Miller, 1998). However, in aggrading systems, plant species can differ in their ability to influence soil aggregation and improve soil productivity by carbon sequestration. For example, (Jastrow, 1987) concluded that an increase in root production and root biomass under C4 prairie graminoids may confer some advantage over introducing C3 Eurasian grasses for the development of water stable aggregates. Switchgrass may improve soil quality by sequestering C in the switchgrass-soil ecosystem owing to its high biomass (Sladden et al., 1991) and deep root system (Ma et al., 2000). However, (Scott, 1998) reported that C4 grasses had no effect on aggregate-size distribution or organic matter concentration in spite of twofold differences in root biomass and threefold differences in N cycling compared to C3 grasses. Similarly, (Corre et al., 1999) concluded that slow accumulation of C4-derived soil organic carbon is an important consideration for its use in restoring riparian and conservation areas. Indeed (Franzluebbers et al., 2000) reported that storage of soil organic carbon occurred at a rate of ~100 g m\(^{-2}\) y\(^{-1}\) during the first 10 years of establishment under grazed tall fescue (C3) and at rate of ~33 g m\(^{-2}\) y\(^{-1}\) under hayed bermudagrass (C4). Ma et al (2000) also concluded that several years of switchgrass culture will be required to realize a soil C sequestration benefit.

In aggrading systems where particulate organic matter (POM) is continually being added to the soil, the destruction of macroaggregates due to the decomposition of POM is offset by the continual input of new POM. Therefore, as the stability of a portion of the macroaggregates is decreasing due to decomposition processes, other macroaggregates are being formed and stabilized, and, moreover, the stabilization of new macroaggregates may
occur at the expense of the breakdown of older less stable macroaggregates (Golchin et al., 1998). The aggregation process itself is a means to both conserve organic matter and allow the stored organic matter to function as a reservoir of plant nutrients and energy. In addition, the role of organic matter in aggregation has major implications for the functioning of soil in regulating air and water infiltration (Carter, 2000). This interaction between SOM and soil aggregates has allowed the development of indicators associated with the process of soil aggregate dynamics and organic matter associated with aggregates. These indicators are useful and convenient for assesses aggrading process in soils (Marquez et al, 2001).

The hypothesis of this study was that 7 years after the conversion of a riparian agricultural row crop system to a C4 buffer system macroaggregate formation would be enhanced in the surface soil. Furthermore the rate of macroaggregate formation would be related to the quantity and quality of organic matter inputs. The purpose of this study was to evaluate the process of soil aggradation following conversion of a riparian agricultural row crop system to a riparian switchgrass filter. The specific objectives were to: (i) to study soil aggregates dynamics through the quantification of stabilization/destabilization, disruption and aggregation using the soil aggregate dynamics, (ii) quantify the carbon associated with soil aggregates, (iii) quantify the various fractions of soil organic matter, and (iv) determine the chemical composition of the light particulate organic matter fraction.

MATERIALS AND METHODS

Site Description

The study sites are located within the Bear Creek, Long Dick Branch, and Keigley Branch watersheds in north central Iowa, USA. More than 85 percent of the area in small
watersheds is devoted to corn-soybean row crop production or intensive grazing (Schultz et al., 1995). The restored buffer was established in 1990 along Bear Creek in areas that had been intensively grazed or cropped with corn and soybeans. The 20-m wide multi-species riparian buffer consists of five rows of streamside poplars (Populus X euramerica) ‘Eugenei’), a row of ninebrak (Physocarpus opulifolius L), a row of redosier dogwood (Cornus sericea L) and a 7.3-m wide strip of switchgrass (Panicum virgatum) closest to the cropped field. The annual corn-soybean rotation cropped plots are located along all three creeks. All of the plots are located on the alluvial floodplain where the dominant soil type is Coland, a fine loamy, mixed, superactive, mesic Cumulic Endoaquoll (DeWitt, 1977).

**Experimental Design and Soil Sampling**

The experimental design was a randomized complete block with three blocks (streams) and two treatments cropped system and 7-year switchgrass. The plot size was approximately 20 x 30 m. Soil samples were collected once a month from May-November in 1997, and in early spring, midsummer, and early fall in 1998. We randomly collected 20 soil cores to a depth of 15 cm from each vegetation type at each stream location using a 5.6 cm steel coring bit for half of the cores and a 2.5 cm bit for the remaining 10 cores. The 10 cores taken with the larger diameter bit were pooled to form one composite sample from each plot to quantify aggregate size distributions and aggregate-associated C. The 10 cores taken with the smaller diameter bit were pooled into one composite sample per plot and used to quantify soil organic carbon fraction. Soil samples were kept cool during transport and were stored in a refrigerator at 4 °C in the laboratory prior to processing and analysis.
Determination of the Aggregate Size Stability Distribution

The aggregate size-stability distribution size-stability aggregate is determined following
the protocol developed by (Marquez, et al., 2001). Field-moist soil is passed through an 8
mm diameter sieve and air-dried. Two, 100 g sub-samples of air-dried soil are used to
determine the aggregate size-stability distribution. One sub-sample is capillary-wetted to soil
moisture a 5% above field capacity and the other is left air-dry. The pretreatments are
referred to as capillary-wetted (pre-wetted soil) and slaked (air-dry soil). Both sub samples
are stored overnight in a refrigerator at 4 °C before wet sieving. Marquez’s (2001) protocol
for the determination of the size stability distribution includes capillary-wetting, slaking, and
subsequent slaking to physically separate soil aggregates depending on their size and
resistance to slaking into four size fractions: (i) fraction one (F1) - large macroaggregates
with diameters greater than 2000 μm, (ii) fraction two (F2) - small-macroaggregates with
diameters between 250-2000 μm, (iii) fraction three (F3) - microaggregates with diameters
between 53-250 μm, and (iv) fraction four (F4) - mineral fraction with diameters smaller than
53 μm. After wet sieving the whole set of fractions is oven-dried at 70 °C. However, the
large and small macroaggregates obtained by the capillary-wetted pretreatment are air-dried
and later used for separation of stable macroaggregates. The amount of sand in each size
fraction is determined by dispersion of a sub-sample of soil aggregates with sodium
hexametaphosphate. The aggregate fractions are ground on a roller mill to pass a 250 μm
sieve and stored at room temperature. Total organic C was quantified using a Carlo-Erba NA
1500 CN analyzer (Haake Buchler Instruments, Paterson, NJ, USA).
Fractionation of Light and Heavy Organic Matter

Light particulate organic matter (LPOM) and heavy particulate organic matter (HPOM) are separated following the experimental method reported by Cambardella and Elliott (1993a) and Gale et al. (2000). Field-moist soil is passed through a 2 mm diameter sieve, the larger pieces of stubble and roots are removed by hand, and the soil is air-dried. A 30 g subsample is dispersed with 100 mL of 5 g L\(^{-1}\) sodium hexametaphosphate by shaking for 15 hr on a reciprocal shaker. The dispersed soil samples are passed through a 53 \(\mu\)m sieve and rinsed several times with water. The material retained on the 53 \(\mu\)m sieve is back-washed onto a 20 \(\mu\)m nylon filter and a vacuum is applied to remove excess water. The material is then rinsed into a 100 mL beaker with sodium polytungstate (1.85 g cm\(^{-3}\)) to a volume of 50 mL. The samples are allowed to separate overnight at room temperature. The following day, the floating material LPOM is aspirated, washed several times with water on a 20 \(\mu\)m nylon filter, and dried at 50 °C. The material that did not float at a density of 1.85 g cm\(^{-3}\) is back-washed onto a 20 \(\mu\)m nylon filter and washed several times with water. The material is rinsed into a 100 mL beaker with sodium polytungstate (2.22 g cm\(^{-3}\)) and allowed to separate overnight at room temperature. The floating material HPOM is aspirated, washed, and dried at 50 °C. Both fractions are finely ground and C is quantified with a Carlo-Erba NA 1500 CN analyzer. Total soil organic C is determined on finely ground sub samples of 2 mm air-dried soil.

Microscopic Observations and Chemical Composition of Organic Matter

Aggregates were examined using scanning electron microscopy (SEM). For SEM observations, aggregates were air-dried, mounted on graphite stubs, and coated with gold
under vacuum in a sputter coater. Solid-state $^{13}$C-NMR spectra of aggregates fractions were acquired at 50.3 MHz using a Varian Unit 200. The NMR spectra were divided into five chemical shift regions according to the chemical types of carbon as follows: 0-46 ppm (alkyl carbon), 46-110 ppm (O-alkyl carbon), 110-164 ppm (aromatic carbon) and 164-190 ppm (carbonyl carbon) (Baldock and Preston, 1995).

**Data Analysis**

The data for 1997 and 1998 were combined because the differences between the two years were not significantly different. All variables were subjected to a one-way analysis of variance for each vegetation type to test for differences between treatments within an aggregate size or organic matter fraction (SAS Institute, 1985). Where significant treatments were observed (P=0.05), contrast analyses were performed to permit separation of means.

The soil aggregate dynamics model is a conceptual model of soil aggregate dynamics that integrates aggregation, disruption, stabilization and destabilization processes of soil aggregates in a framework that permits studying soil aggregate dynamics over time or comparing ecosystems such as aggrading, degrading or steady-state systems (Marquez et al., 2001). The soil aggregate dynamics model is based on aggregates resistance to slaking and assesses aggregate dynamics through the use of the aggregate size-stability distributions of a reference ecosystem and the new or actual aggregate size-stability distributions that result after natural or human perturbations. Therefore, soil aggregate dynamics are probed in terms of the processes that should take place in order to bring the system from a reference or initial state to a final or new state (Figure 1). Values in the aggregate size-stability distribution that
are associated with the reference state are identified using the subscript $n$ and values associated with the new state are referenced using the subscript $n + 1$.

The soil aggregate dynamics model entails three major steps: (i) are unstable macroaggregates (> 250 µm) associated with the reference state are disrupted by a major perturbation, (ii) aggregate constituent units that result from the disruption and stable aggregates from the reference state are allocated to size fractions belonging to the monitored (new) state, and (iii) the net change in the amount of aggregates in each size fraction, that should occur in order to bring the system to the final state is calculated. This net change is calculated and interpreted in terms of allocation rules based on three basic processes underlying the dynamics of soil aggregates: (i) disruption, (ii) stabilization and destabilization, and (iii) aggregation. Although we present all the equations and definitions involved in this particular study, the reader should bear in mind that the required equations could change depending on the particular scenario.

Figure 1 shows the different pathways associated with dynamics of soil aggregates. Intrinsic model variables are given in Table 1 and convenient indexes are given in Table 2. The soil aggregate dynamics model is extended to the analysis of the carbon associated with soil aggregate dynamic pathways (Figure 2). Therefore we use the label C-soil aggregate to emphasize that we are studying carbon associated with soil aggregate dynamics using the soil aggregate dynamics model. Intrinsic C-SAD model variables are in Table 3 and indicators and indices are in Table 4.
RESULTS AND DISCUSSION

In this study, we used a cropped system as a previously cultivated soil that was converted to a riparian forest buffer according to the USDA Natural Resources Conservation Service Conservation Practice Standard 393 (USDA-NRCS, 1997). The riparian forest buffer standard, in Iowa, consists of two distinct functional zones. Zone 1 begins at the stream bank edge of the active channel and extends a minimum distance of 10.7 m, with trees and/or shrubs. Zone 2 begins at the up-gradient edge of Zone 1 and extends 6.1 to 36.6 m perpendicular to Zone 1. Native warm season grasses and forbs are recommended for vegetation in zone 2 (USDA-NRCS, 1997). In this study Zone 2 was established in 1990 using a 7 m wide switchgrass filter (*Panicum virgatum* L. cv. Cave-n-Rock).

Size-Stability Distribution

The results are expressed as percentage of soil aggregate in each fraction after sand correction (Table 5). The aggregate size-stability distribution shows that there are no significant differences in the amount of soil present as stable large and small macroaggregates under cropp and switchgrass, respectively. In addition, the amount of unstable large macroaggregates under switchgrass is 13% greater than under ARC. Conversely, the amount of unstable small macroaggregates under switchgrass is 20% less than under cropped. Silt clay (< 53μm) was not significantly different under switchgrass compared to cropped system.
Soil Aggregates Dynamics

As a result of the perturbation of soil under the cropped system to establish a switchgrass filter, unstable large macroaggregates $U_1 = 29.3$ are disrupted and 73% of the material released is allocated as small macroaggregates $G_{2,n} = 21.4$. From this amount 19.6 ($y_{2G}$) is allocated as unstable small macroaggregates and 1.8 ($x_{2G}$) as stable small macroaggregates. Disruption of unstable small macroaggregates from ARC ($U_2 = 14.2$) is allocated to F3 and F4 (Figure 3).

Figure 5 shows that 100% ($a_1 = 4.0\%$) of stable large macroaggregates and 100% ($a_2 = 22.3$) of the stable small macroaggregates in the cropped system remain as stable small macroaggregates in the new state, switchgrass. Therefore, none of the stable macroaggregates are destabilized ($b_1 = 0$ and $b_2 = 0$). Microaggregates, which are by definition stable, remain.

To assess aggregation and disruption the SAD model uses the net-flux (NF). The net-flux is a number that can be positive or negative. Positive values are interpreted as new aggregates coming into and negative values as aggregates going out of a fraction. Aggregates can come into a fraction as a result of the aggregation of smaller aggregate constituent units or the disruption of larger aggregates (Figure 1). Similarly, aggregates can go out of the fraction by aggregation and formation of new bigger aggregates or alternatively by the disruption and formation of smaller aggregates. Figure 3 shows that the net flux of large macroaggregates (>2000μm) is positive ($NF_{1,n+1} = 34.7$), which results in the formation of new stable ($x_1$) and unstable ($y_1$) large macroaggregates. The newly formed large macroaggregates are mainly unstable ($y_1 = 33.1$) and with only a small fraction stabilized ($x_1 = 1.6$). In addition, $NF_{2,n+1}$ is negative ($NF_{2,n+1} = -9.8$), the $NF_{2,n+1}$ is derived from $x_2$.
and $y_2$, which represent the contribution from $G_{2,n+1}$ and from $NF_{2,n+1}$. Thus $x_2 = x_{2G} + x_{2NF}$ and $y_2 = y_{2G} + y_{2NF}$, see Figure 1 and Table 1. In these equations $x_{2G}$ is the amount of stable small macroaggregates (250–2000 µm) that result from disruption of unstable large macroaggregates (>2000 µm). Similarly $y_{2G}$ is the amount of unstable small macroaggregates that result from disruption of unstable large macroaggregates thus, $G_{2,n} = x_{2G} + y_{2G}$. Also $x_2$ and $y_2$ are the amount of stable and unstable macroaggregates that build-up the net flux $NF_{2,n+1}$, thus, $NF_{2,n+1} = x_2 + y_2$. Disruption of the unstable large macroaggregates resulted in a total gain of small macroaggregates ($G_{2,n} = 21.4$), that are allocated to F2 (250-2000 µm), however, only 1.8% ($x_{2G} = 1.8$) of these were allocated as stable small macroaggregate and the rest were allocated as unstable small macroaggregates ($y_{2G} = 19.6$). In addition, Figure 3 and Table 1 show that $x_{2,NF} = 0$ and $y_{2,NF} = -9.8$ and they are the amount of stable and unstable macroaggregates that build-up the net flux $NF_{2,n+1}$.

Thus, $NF_{2,n+1} = x_{2,NF} + y_{2,NF}$ and $NF_2 = -9.8$. The $NF_{3,n+1} = S_{3,n+1} - (S_{3,n} + G_{3,n})$ and $NF_3 = -11.1$. The $NF_{4,n+1} = S_{4,n+1} - (S_{4,n} + G_{4,n})$ and $NF_{4,n+1} = -13.8$.

Therefore, the dynamics are interpreted as some small macroaggregates ($NF_{2,n+1} = -9.8$) joining with microaggregates ($NF_{3,n+1} = -11.1$) and silt+clay particles ($NF_{4,n+1} = -13.8$) to form new large macroaggregates, that are reflected in a positive net-flux of unstable large macroaggregates to F1 ($NF_{1,n+1} = 34.7$).
Monitoring Aggregate Dynamics

An important advantage of the conceptual framework used by the SAD model is that it allows definition of convenient indexes to assess and monitor soil aggregate dynamics. These indices and their definitions are given Table 2.

*Disruption index (DI)* - Is the relative amount of unstable macroaggregates (>250 μm) with respect to the total amount of soil aggregates in the state being considered. The \( DI_{arc} = 44 \) in the reference state (cropped system) and \( DI_{CSF} = 43 \) after the conversion to the switchgras. This result indicates that 44% and 43% of the unstable macroaggregates, respectively, can potentially be disrupted and their constituent units redistributed into smaller aggregate size fractions.

*Formation Indices of Stable macroaggregates (FIS) and Formation Indices of Unstable macroaggregates (FIU)* – These indexes are defined as the relative amount of stable and unstable aggregates that result from a positive net flux. Our results indicate that seven years after the establishment of the switchgrass, 95% of the newly formed large macroaggregates are unstable \( FIU_1 = 0.95 \) and only 5% are stable \( FIS_1 = 0.05 \). Similarly, 84% of the newly formed small macroaggregates are unstable \( FIU_2 = 0.84 \) and 16% are stable \( FIS_2 = 0.16 \).

*Destabilization of Stable Macroaggregates (DSM) and Stabilization of Stable Macroaggregates (SSM)* – Destabilization of stable macroaggregates is the relative amount of stable macroaggregates that remain in the same size fraction but become unstable macroaggregates. Stabilization of stable macroaggregates is the relative amount of stable macroaggregates that remain in the same fraction as stable macroaggregates. The results indicate that none of the stable large and small macroaggregates are destabilized \( DSM_1 = 0 \)
and $DSM_2 = 0$) and as a consequence they remain in the same fraction as stable large and small macroaggregates ($SSM_1 = 1$ and $SSM_2 = 1$) after the conversion of cropped system to switchgrass.

The total (net) Aggregation-Disruption Index (ADI) - The soil aggregate dynamics model uses aggregation-disruption index and quantitatively evaluate the "net" dominant soil aggregate processes, that drives soil aggregate dynamics upon the establishment of switchgrass. Our analysis renders $ADI = 0.03$. Qualitatively, the positive sign of $ADI$ indicates that the "net" process that leads to the new state is aggregation, which yields 3% increase in new macroaggregates. This result suggests that there is a slow but consistent shifting of the aggregate size distribution to larger aggregate sizes.

Note that the ratio between the amount of stable and unstable large macroaggregates (SLM/ULM) is 0.14 under cropped system and 0.17 under switchgrass. We observed the opposite pattern in the ratio between stable and unstable small macroaggregates (SSM/USM), which is 1.57 under cropped system, and 2.41 under switchgrass. It is clear from these results that the perennial nature of the switchgrass favors the formation of large macroaggregates under switchgrass. In contrast, under cropped system tillage increases soil aggregate break down (disruption) and stabilization processes are inhibited. Our results show that none of the stable macroaggregates have been destabilized during the conversion of cropped system to switchgrass. We speculate that the lack of disruption, by tillage under the established switchgrass promotes the formation of new large macroaggregates that are mainly unstable.
Carbon Associated with Soil Aggregates

The study of carbon associated with soil aggregate dynamics is also based on the three processes considered in the soil aggregate dynamics model (Figure 2) (Marquez et al. 2001). In this specific case, the conceptualization of the soil aggregate dynamics model is extended to include the amount of carbon associated with aggregates. Figure 4 shows that upon the disruption of unstable large macroaggregates there is 6.5 mg C g\(^{-1}\) of soil associated with the material released, 4.2 of this amount is allocated to small macroaggregates and 2.3 mg C g\(^{-1}\) is associated with aggregates < 250 µm.

Figure 4 shows that 100% (\(Ca_1 = 1.3\) mg C g\(^{-1}\)) of the C associated with stable large macroaggregates remains as carbon associated with stable large macroaggregates \(Ca_1\) and none (\(Cb_1 = 0.0\)) of the carbon associated with stable large macroaggregates becomes associated with unstable large macroaggregates (\(Cb_1\)). Also 100% (\(Ca_2 = 6.0\) mg C g\(^{-1}\)) of the carbon associated with stable small macroaggregates remains as carbon associated with stable small macroaggregates \(Cb_2\) and none (\(Cb_2 = 0\) mg C g\(^{-1}\)) of the carbon associated with stable small macroaggregates becomes associated with aggregates that became unstable in the same fraction after the establishment of switchgrass.

The net-flux of carbon in F1 is positive and equal to \(CNF_1 = 6.9\) mg C g\(^{-1}\). Carbon net flux in F2, F3, and F4 are equal to \(CNF_2 = -0.6\), \(CNF_3 = -2.5\), and \(CNF_4 = -2.3\) mg C g\(^{-1}\). Moreover, the total associated carbon net flux is positive and equal to \(TCNF = +1.5\) mg C g\(^{-1}\) (Figure 4). This result indicates that seven years after the conversion of cropped system to switchgrass soil aggregates have gained and stored a net additional amount of carbon equal to 1.5 mg C g\(^{-1}\).
Monitoring Associated Carbon to Soil Aggregate Dynamics

Several indicators are defined to assess and monitor carbon associated with soil aggregate dynamics: (Equations in Table 4 and the results in Table 8).

*Carbon Associated with Disruption (CD)* - The amount of carbon associated with unstable macroaggregates (>250 μm) is the carbon associated with the disruption processes. Table 8 shows that $CD_{ARC} = 9.44 \text{ mg C g}^{-1}$ for the reference state and $CD_{SGF} = 10.00 \text{ mg C g}^{-1}$ for the new ecosystem switchgrass.

*Associated Carbon to Formation of Stable Carbon Associated with the Formation of Stable Aggregates (CFS) and Carbon Associated with the Formation of Unstable Aggregates to Formation of Unstable (CFU)* – These indicators are defined as the amount of carbon associated with new stable and new unstable macroaggregates. Table 8 shows that $CFS_1 = 0.03$ and $CFU_1 = 0.97$ which indicates that 3% of the carbon associated with new large macroaggregates is exclusively associated with new stable large macroaggregates and 97% is associated with new unstable large macroaggregates. Similar patterns are observed in F2 where $CFS_2 = 0.09$ and $CFU_2 = 0.91$.

*Carbon Associated with Destabilization of Stable Macroaggregates (CDSM) and to Stabilization of Stable Macroaggregates (CSSM)* – Table 8 shows that $CDSM_1 = 0$ and $CSSM_1 = 1$. This suggests that all the carbon that was associated with the stable large macroaggregates remains in stable large macroaggregates and none has been destabilized during the conversion of the cropped system to switchgrass. In addition, Table 8 shows that $CDSM_2 = 0$ and $CSSM_2 = 1$. Therefore all carbon that was associated with stable small macroaggregates also remains associated with stable small macroaggregates. These indices
indicate that none of the carbon sequestered in stable macroaggregates has been exposed to either predation or oxidation, which in turn suggests that in spite of the perturbation sequestered carbon is still physically protected. This perturbation was a one time disturbance of the soil surface during drilling of switchgrass seed. Over the following 7 years no surface disturbance took place reducing the opportunity for oxidation.

*Carbon Associated with Aggregation and Disruption (CAD)* - The \( \text{CAD} = 1.1 \text{ mg C g}^{-1} \) (Table 8) indicates that there are 1.1 mg C g\(^{-1}\) associated with the 3% of new macroaggregates \( \text{ADI} = 0.03 \) yielded by the "net" process that leads to the new state seven years after the conversion from cropped system to switchgrass. The results indicate that although there is a significant amount of new macroaggregate formation they are mainly unstable macroaggregates. Seven years after the restoration no significant formation of new stable macroaggregates has occurred. The amount and relative instability of these new macroaggregates suggests that physical protection of inter-microaggregate binding agents inside the macroaggregates may not be a major mechanism influencing C sequestration in this switchgrass ecosystem in the short term.

SEM micrographs presented in Figure 8 show evidence that under cropped system, particulate organic matter is not homogeneously mixed in the soil matrix. Because it has little prior association with soil particles it provides little binding for the particles, which is reflected in the susceptibility of the aggregates to disruption when they are slaked. Figure 8 also shows the presence of coarse switchgrass roots without a network of fine roots and hyphae such as was reported under C3 grasses (Marquez et al., 2001). Marquez et al. (2001) show evidence of the presence of very fine roots, root hairs, and hyphae form an extensive
network around the large macroaggregates (> 2000μm) which entangle particles and microaggregates into macroaggregates, that are then stabilized under a C3 grass (Figure 8).

**Organic Carbon Fractions**

Total soil organic C in the switchgrass plots is no significantly different (22.8 mg C g⁻¹) than (21.4 mg C g⁻¹) under the cropped system. The C content associated with the mineral-fraction had the same pattern as the total soil organic C in the whole soil (Figure 5). When averaged across years (1997-1998), no significant differences in total particulate organic matter-C content was observed between switchgrass (1.71 mg C g⁻¹) and cropped system (1.66 mg C g⁻¹) (Figure 6). The amount of total particulate organic matter-C under switchgrass and cropped system account for 7% and 8%, respectively, of the total organic C (Figure 6). In addition, no significant differences are observed between switchgrass and cropped system in the light particulate organic matter-C and the heavy particulate organic matter-C (Figure 6). The amount of light particulate organic matter-C under the switchgrass and cropped system account for 81% of the total particulate organic matter-C. Our results reveal that the 7-year old switchgrass has gained 1.4 mg C g⁻¹ of total organic carbon but this amount is not significantly different than the total amount of organic carbon in soil aggregates under the cropped system. This result is in agreement with the total net flux of C calculated using the soil aggregate dynamics model. No significant differences were found in the amount of total, light and heavy particulate organic matter between the switchgrass and cropped system seven years after establishment of the switchgrass.

The relative proportions of the NMR spectra of different types of carbon are shown in Figure 7. The major signal for the light particulate organic matter (<1.85 g cm⁻³), obtained
by the fractionation procedures described above, was from the 46-110 ppm region (O-alkyl carbon) with peaks at 74 ppm, indicating that carbohydrates are quantitatively the most significant compounds in this organic matter fraction. These spectra accounted for 52 and 59% of the total area under the NMR spectra for samples from the cropped system during July and November, respectively. Under the switchgrass the O-alkyl carbon accounted for 64 and 59% of the total area under the NMR spectra during July and November, respectively. However, under switchgrass the signal intensity of O-alkyl carbon was not only associated with carbohydrates but also with other structural units. The contribution of alkyl and aromatic carbon were much smaller (13-29%) except, that alkyl carbon accounted for 46% during July 1998 under cropped system. The carbonyl carbon occurred in the lowest quantities (2-6%). The result from the NMR analysis confirms the hypothesis that the light particulate organic matter-C is a fraction that is composed of partially decomposed organic matter. Changes in the ratio of O-alkyl to alkyl carbon over time have been used to understand decomposition processes (Baldock and Preston, 1995). The ratio of O-alkyl to alkyl carbon was lower in July (0.48) and increased in November (0.90) under cropped system. The lower ratio during July is associated with a higher decomposition rate that is associated with the loss of the most easily metabolized carbohydrates and the accumulation of alkyl C (Preston, 1996). In November the amount of carbon in the alkyl structure decreases reflecting an increase in the amount of carbon in O-alkyl structure. However, the results suggest a slower decomposition of O-alkyl carbon in the switchgrass soils compared with the cropped system soils, because the ratio of O-alkyl to alkyl C does not change over time in July (0.50) and increases in November (0.55). The lower decomposition rate observed under switchgrass suggests that the presence of lignin, which is much more
resistant to decomposition, plays an important role in the chemical composition of the light particulate organic matter-C under the switchgrass. Lignin contents, and lignin-N, are primary factors controlling the rate of organic matter decomposition in terrestrial ecosystems (Parton et al., 1987). Akin (1989) reported lignin values twice are almost twice as high in C4 than in C3 grasses (8.4 vs. 4.3 respectively). Consistent with these results we found a higher C/N light particulate organic matter-C ratio under switchgrass (~18-20) than under cropped system (~14-15).

Weaver and Zink (1946); found that the roots of warm-season prairie grasses (C4) are generally coarser, longer-lived and more resistant to decay than the roots of cool season grass (C3). In addition, Hetrick et al., (1998a) and Hetrick et al., (1998b) observed that warm-season grasses (C4) have coarser root systems with, fewer primary roots of larger diameters. Tufekcioglu et al., (1999) working in the same research area used in this study, reported that switchgrass (C4) had significantly higher amounts (1248 kg ha\(^{-1}\)) of dead fine roots in the top 0-35cm of soil than under cropped fields (650 kg ha\(^{-1}\)), but lower than under cool-season grass (C3) (2225 kg ha\(^{-1}\)). In contrast the amount of live small root biomass was highest under switchgrass (1861 kg ha\(^{-1}\)) compared with (393 kg ha\(^{-1}\)) under cool-season grass and (207 kg ha\(^{-1}\)) under cropped systems. Pickle, (1999) also working in the same experimental area used in this study, reported that eight years after establishment of the switchgrass (C4) filter the amount of biomass-C was 161 mg C kg soil\(^{-1}\) compared with 100 mg C kg soil\(^{-1}\) under the cropped system. In both systems the amount of biomass-C was significantly lower than under cool-season grass (C3) (327 mg C kg soil\(^{-1}\)).

Scott (1998) observed that a threefold difference in root biomass among the grass species did not alter the proportion of macroaggregates or the amount of C associated with
aggregates 10 years after establishment of Fergus Falls grass (C4). (Franzluebbers et al., 2000) reported that soil organic matter and total N, to a depth of 200 mm, was accumulated at greater rates under grazed tall fescue (C3) than under bermudagrass (C4) and that storage of soil organic C occurred at a rate of ~100 g m\(^{-2}\) y\(^{-1}\) during the first 10 years of establishment under fescue (C3) grasses and at a rate of ~33 g m\(^{-2}\) y\(^{-1}\) under grazed bermudgrass (C4). In our study, the storage of soil organic C under switchgrass occurs at a rate of ~43 g m\(^{-2}\) y\(^{-1}\), which is comparable with the storage rate reported by Franzluebbers, et al. (2000) for C4 grasses. Ma et al., (2000) reported that management practices such as N application, row spacing, and harvest frequency did not alter soil C concentrations in the 2 to 3 years following establishment of switchgrass, in long term (10 yr), however, 10 years after establishment the switchgrass had sequestered more soil C than an adjacent fallow soil. Ma et al., (2000) concluded that switchgrass will accumulate soil C, but it may take several years before any increases are detectable. Corre et al., (1999) concluded that it took 16 to 18 years after planting for the total SOC under C4 grass to approach a level similar to that under the original C3 grass.

Our results show that seven years after the establishment of switchgrass no destabilization of macroaggregates occurs. In addition, new aggregate formation consisted mainly of unstable large macroaggregates that resulted from the aggregation of smaller fractions. Several mechanisms can support our results: (i) coarse roots (Hetrick et al., 1998a; Hetrick et al., 1998b); (ii) longer lived and more resistant to decay roots (Weaver and Zink, 1946); (iii) lower biomass- C (Pickle, 1999), (iv) lower rates of mineralization (Pickle, 1999), (v) lower amounts of light and heavy particulate organic mater; (vi) no changes in the ratio of alkyl-C/O-alkyl-C carbon, over time; and (vii) light POM-C with a high C/N ratio.
All of these factors together do not support the hypothesis that switchgrass favors the formation of stable macroaggregates and sequestering of carbon in the short term. The perennial nature of switchgrass suggests that this native grass could have the potential to stabilize newly unstable small and large macroaggregates if the binding agents related with the inputs of organic matter increase as a consequence of an increase in the rate of residue decomposition over time. However, several researchers have reported that SGF can have positive effects in short term restoration of riparian zones because the living root systems of switchgrass remain in the soil to support regeneration of aboveground plant parts, and thus represent a continuous pool of stored carbon (Ma et al., 2000; Tufekcioglu et al., 1999). In addition, the extensive root system of switchgrass is particularly effective in reducing nitrate-nitrogen loss in soil, the amount removed by switchgrass from the soil profile below 120 cm was 20 kg ha\(^{-1}\) per year (Huang et al., 1996). N immobilization has also been measured during winter months (Pickle, 1999). Other important benefits of switchgrass are their effectiveness in reducing transport of sediment. Lee et al., (1999) reported that a 7.1 m wide switchgrass buffer alone was able to remove 95% of the sediment and 80% of sediment-bound nutrients from adjacent row crop field runoff.

In contrast under cropped system, every year soil perturbations inhibit the formation of new stable large and small macroaggregates and promote the disruption of unstable large and small macroaggregates exposing particulate organic matter that had been protected and resulting in a loss of soil organic matter that further destabilized the stable macroaggregates. These degradable processes jeopardize the soil’s capacity to function as a healthy riparian ecosystem. These riparian zones are play an important role in stabilizing stream banks,
provide sediment storage, serve as nutrient sinks for the surrounding watershed and improve the quality of water leaving the watershed.

**CONCLUSIONS**

The results indicate that seven years after the conversion of an cropped system to a switchgrass filter, the net predominant process is aggregation that leading to a 3% of increase in macroaggregates. Most of these new macroaggregates are unstable. In addition, our results indicate that there is 1.1 mg C g⁻¹ of soil associated with the new macroaggregates. None of the previously stable large and small macroaggregates present under the cropped system were destabilized by the conversion of the cropped system to switchgrass. This is one of the important and beneficial points to be highlighted in restoration of grass filter systems. In our study the destabilization of stable macroaggregates that occurs under the continuous cropped system has topped due to the introduction of the perennial switchgrass.

The relative instability of the new-formed macroaggregates suggests that the chemical composition of the light particulate organic matter and the inputs of light particulate organic matter and heavy particulate organic matter play an important role in stabilizing macroaggregates. Indeed, the lower decomposition rates observed under switchgrass suggest that the presence of lignin, which is resistant to decomposition, plays an important role in the chemical composition of the light particulate organic matter-C under switchgrass. The results suggest a slower decomposition of O-alkyl carbon in the switchgrass soils compared with the cropped system soils, the ratio of O-alkyl to alkyl C does not change over time in July (0.50) and in November (0.55).
In our study, the storage of soil organic C under switchgrass during the seven years occurred at a rate of $-43 \text{ g m}^{-2} \text{ y}^{-1}$. This storage rate is comparable with the rate of carbon storage reported by (Franzluebbers, et al. 2000) for C4 grasses during a 10 year period but lower than the rate of storage under C3 grasses ($-100 \text{ g m}^{-2} \text{ yr}^{-1}$).

There were no significant differences in total, light and heavy particulate organic matter between the cropped system and the seven-year-old switchgrass. Our study indicates that the presence of: (i) coarse roots, (ii) higher C/N ratios in the light particulate organic matter, (iii) lower inputs of total; particulate organic matter, and (iv) no changes in the alkyl-C/O-alkyl-C carbon ratio over time. These observations support the hypothesis that switchgrass favors slow carbon sequestration, which in turn hinders the formation of stable macroaggregates in soil in the short-term and jeopardizes the short-term effectiveness of switchgrass as a riparian filter of soluble chemicals. However, switchgrass role in slowing surface runoff and trapping sediment and for providing wildlife habitat provide positive benefits early in the restoration process.

REFERENCES


Figure 1. Dynamic pathways for soil aggregates using the soil aggregate dynamics (SAD) model (Marquez et al., 2001). $S =$ stable aggregates, $U =$ unstable aggregates, $NF =$ net flux, $G =$ gains, $x =$ new stable macroaggregates when $NF > 0$, $y =$ new unstable macroaggregates when $NF > 0$, $a =$ stable macroaggregates that remain stable, and $b =$ stable macroaggregates that become unstable, $n =$ reference state, $n+1 =$ new stat.
Figure 2. Carbon associated with the dynamic pathways of aggregate $CS = $ carbon associated with stable aggregates, $CU = $ carbon associated with unstable aggregates, $CNF = $ carbon associated with net flux, $CG = $ carbon associated with gains, $Cx = $ carbon associated with new stable macroaggregates, $Cy = $ carbon associated with new unstable macroaggregates, $Ca = $ carbon associated with stable macroaggregates that remain stable, and $Cb = $ carbon associated with stable macroaggregates that become unstable, $n = $ reference state, $n+1 = $ new state.
Figure 3. Dynamic pathways of aggregates using the annual row cropped system as the reference system and the riparian switchgrass filter as a new aggrading system. Values are pooled data from 1997 and 1998 expressed on a sand-free basis as % of soil aggregates ± 0.1 in each size fraction. $S$ = stable aggregates, $U$ = unstable aggregates, $NF$ = net flux, $G$ = gains, $x$ = new stable macroaggregates when $NF > 0$, $y$ = new unstable macroaggregates when $NF > 0$, $a$ = stable macroaggregates that remain stable, and $b$ = stable macroaggregates that become unstable.
Figure 4. Dynamics of soil organic carbon associated with aggregates to a depth of 15 cm in a riparian annual row crop system (ARC) and a riparian switchgrass filter system (SGF). Values are pooled data from 1997 and 1998 expressed in mg C g⁻¹ (± 0.1). Values inside of parenthesis are aggregate carbon concentration expressed as mg C g⁻¹ sand-free aggregates. CS = carbon associated with stable aggregates, CU = carbon associated with unstable aggregates, CNF = carbon associated with net flux, CG = carbon associated with gains, Cx = carbon associated with new stable macroaggregates, Cy = carbon associated with new unstable macroaggregates, Ca = carbon associated with stable macroaggregates that remain stable, and Cb = carbon associated with stable macroaggregates that become unstable.
Figure 5. Total organic carbon and mineral fraction-C expressed in mg C g⁻¹ (whole soil) at a depth of 0-15 cm under annual row cropped (ARC) and switchgrass filter (SGF). Different letters indicate differences (P<0.05) between vegetation treatments within a size class.
Figure 6. Total particulate organic matter carbon (TPOM-C), light particulate organic matter carbon (LPOM-C) and heavy particulate organic matter carbon (HPOM-C) at a depth of 0-15 cm under annual row cropped field (ARC) and 7-y switchgrass filter (SGF). Different letters indicate differences (P<0.05) between vegetation treatments within size class.
Figure 7. The relative proportions of different types of carbon in LPOM-C at a depth of 0 – 15 cm under riparian switchgrass filter (SGF) and a non-buffered annual row cropped field (ARC).
Figure 8. Macroaggregates > 2000 μm showing sand particles encrusted with an agglomeration of smaller macroaggregates and microaggregates and close-up of plant fragments associated with inorganic soil particles under cropped system (a-d). Macroaggregates > 2000 μm showing sand particles encrusted with an agglomeration of smaller macroaggregates and microaggregates and close up of coarse root associated with inorganic soil particles in SGF (e-h). Macroaggregates > 2000 μm composed of many microaggregates bound with a fine roots under cool-season grass (i-l) hyphae and roots and magnification of a hyphae of a root-associated fungus interconnecting particles in a fine loamy soil from under long established riparian cool-season grass filter from Bear Creek Iowa.
Table 1. Summary of intrinsic variables involved in the soil aggregates model. The reader should be aware that some of the equations could change if the scenario is different. $S =$ stable aggregates, $U =$ unstable aggregates, $NF =$ net flux, $G =$ gains, $x =$ new stable macroaggregates when $NF > 0$, $y =$ new unstable macroaggregates when $NF > 0$, $b =$ stable macroaggregates that become unstable, $T$ is total percentage of soil aggregates, $n =$ reference state, and $n + l =$ new state.

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Table 2. Summary of indices used by the soil aggregates model to assess soil aggregate dynamics. FIS = formation index of stable macroaggregates. FIU = formation index of unstable macroaggregates. DSM = Index of destabilization of macroaggregates. SSM = Stabilization of stable macroaggregates. $x_2 = \text{net-change of stable macroaggregates.}$ $y_2 = \text{net-change of unstable macroaggregates.}$ DI = disruption index. A = represents the amount of aggregates that result for aggregation. d = disruption. ADI = aggregation-disruption index.

<table>
<thead>
<tr>
<th>Index</th>
<th>Conditions</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$DI_n = DI_{ARC}$</td>
<td></td>
<td>$DI_{ARC} = \left( \frac{U_{1,n} + U_{2,n}}{T_n} \right) \times 100$</td>
</tr>
<tr>
<td>$DI_{n+1} = DI_{SGF}$</td>
<td></td>
<td>$DI_{SGF} = \left( \frac{U_{1,n+1} + U_{2,n+1}}{T_{n+1}} \right) \times 100$</td>
</tr>
<tr>
<td>$FIS_1$</td>
<td>$NF_{1,n+1} &gt; 0, x_1 &gt; 0$</td>
<td>$FIS_1 = \frac{x_1}{NF_{1,n+1}}$</td>
</tr>
<tr>
<td>$FIU_1$</td>
<td>$NF_{1,n+1} &gt; 0, y_1 &gt; 0$</td>
<td>$FIU_1 = \frac{y_1}{NF_{1,n+1}}$</td>
</tr>
<tr>
<td>$FIS_2$</td>
<td>$\left( G_{2,n} + NF_{2,n+1} \right) &gt; 0, x_2 &gt; 0$</td>
<td>$FIS_2 = \frac{x_2}{\left( G_{2,n} + NF_{2,n+1} \right)}$</td>
</tr>
<tr>
<td>$FIU_2$</td>
<td>$\left( G_{2,n} + NF_{2,n+1} \right) &gt; 0, y_2 &gt; 0$</td>
<td>$FIU_2 = \frac{y_2}{\left( G_{2,n} + NF_{2,n+1} \right)}$</td>
</tr>
<tr>
<td>$DSM_1$</td>
<td>$S_{1,n} &gt; 0$</td>
<td>$DSM_1 = \frac{b_1}{S_{1,n}}$</td>
</tr>
<tr>
<td>$SSM_1$</td>
<td>$S_{1,n} &gt; 0$</td>
<td>$SSM_1 = \frac{a_1}{S_{1,n}}$</td>
</tr>
<tr>
<td>$DSM_2$</td>
<td>$S_{2,n} &gt; 0$</td>
<td>$DSM_2 = \frac{b_2}{S_{2,n}}$</td>
</tr>
<tr>
<td>$SSM_2$</td>
<td>$S_{2,n} &gt; 0$</td>
<td>$SSM_2 = \frac{a_2}{S_{2,n}}$</td>
</tr>
<tr>
<td>A</td>
<td>$NF_{1,n+1} &gt; 0, NF_{2,n+1} &lt; 0, NF_{3,n+1} &lt; 0, NF_{4,n+1} &lt; 0$</td>
<td>$A = NF_{1,n+1}$</td>
</tr>
<tr>
<td>d</td>
<td>$NF_{1,n+1} &gt; 0, NF_{2,n+1} &lt; 0, NF_{3,n+1} &lt; 0, NF_{4,n+1} &gt; 0$</td>
<td>$d = 0$</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>$NF_{2,n+1} &lt; 0$</td>
<td>$\alpha = x_2 + y_2$</td>
</tr>
<tr>
<td>ADI</td>
<td></td>
<td>$ADI = \frac{\left( A + \alpha \right) - \left[ DI_n + d \right]}{T_{n+1}}$</td>
</tr>
</tbody>
</table>
Table 3. Summary of intrinsic variables involved in the soil aggregate dynamics model studying the associate carbon. The reader should be aware that some of the equations could change if the scenario is different. $CS =$ carbon associated with stable aggregates, $CU =$ carbon associated with unstable aggregates, $CNF =$ carbon associated with net flux, $CG =$ carbon associated with gains, $Cx =$ carbon associated with new stable macroaggregates, $Cy =$ carbon associated with new unstable macroaggregates, $Ca =$ carbon associated with stable macroaggregates that remain stable, and $Cb =$ carbon associated with stable macroaggregates that become unstable, $TCNF =$ total C associated with net flux, $n =$ reference state, and $n+1 =$ new state.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Conditional</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Ca_1$</td>
<td>$S_{1,n} &lt; S_{1,n+1}$</td>
<td>$Ca_1 = CS_{1,n}$</td>
</tr>
<tr>
<td>$Cb_1$</td>
<td>$S_{1,n} &lt; S_{1,n+1}$</td>
<td>$Cb_1 = 0$</td>
</tr>
<tr>
<td>$Cx_1$</td>
<td>$S_{1,n} &lt; S_{1,n+1}$</td>
<td>$Cx_1 = CS_{1,n+1} - Ca_1$</td>
</tr>
<tr>
<td>$Cy_1$</td>
<td></td>
<td>$Cy_1 = CU_{1,n+1} - Cb_1$</td>
</tr>
<tr>
<td>$CNF_{1,n+1}$</td>
<td></td>
<td>$CNF_{1,n+1} = Cx_1 + Cy_1$</td>
</tr>
<tr>
<td>$Ca_2$</td>
<td>$S_{2,n} &lt; S_{2,n+1}$</td>
<td>$Ca_2 = CS_{2,n}$</td>
</tr>
<tr>
<td>$Cb_2$</td>
<td>$S_{2,n} &lt; S_{2,n+1}$</td>
<td>$Cb_2 = 0$</td>
</tr>
<tr>
<td>$Cx_2$</td>
<td>$S_{2,n} &lt; S_{2,n+1}$</td>
<td>$Cx_2 = CS_{2,n+1} - Ca_2$</td>
</tr>
<tr>
<td>$Cy_2$</td>
<td></td>
<td>$Cy_2 = CU_{2,n+1} - Cb_2$</td>
</tr>
<tr>
<td>$Cx_{2G}$</td>
<td>$</td>
<td>x_2</td>
</tr>
<tr>
<td>$Cy_{2G}$</td>
<td>$</td>
<td>x_2</td>
</tr>
<tr>
<td>$Cx_{2NF}$</td>
<td>$</td>
<td>x_2</td>
</tr>
<tr>
<td>$Cy_{2NF}$</td>
<td>$</td>
<td>x_2</td>
</tr>
<tr>
<td>$CNF_{2,n+1}$</td>
<td></td>
<td>$CNF_{2,n+1} = Cx_{2NF} + Cy_{2NF}$</td>
</tr>
<tr>
<td>$CNF_{3,n+1}$</td>
<td></td>
<td>$CNF_{3,n+1} = CS_{3,n+1} - (CS_{3,n} + CG_{3,n})$</td>
</tr>
<tr>
<td>$CNF_{4,n+1}$</td>
<td></td>
<td>$CNF_{4,n+1} = CS_{4,n+1} - (CS_{4,n} + CG_{4,n})$</td>
</tr>
<tr>
<td>$TCNF$</td>
<td></td>
<td>$TCNF = \sum_{i=1}^{4} CNF_{i,n+1}$</td>
</tr>
</tbody>
</table>
Table 4. Summary of indicators and indices used by the SAD model to assess associated carbon to soil aggregate dynamics. CD = carbon associated with unstable macroaggregates. CFIS = carbon associated to formation of stable, CFIU = associated carbon to formation of unstable, CSSM = carbon associated with stabilization, and CDSM = carbon associated with destabilization, Cx = carbon associated with new stable macroaggregates, Cy = carbon associated with new unstable macroaggregates, CAD = carbon associated with aggregation and disruption, CS = carbon associated with stable aggregates, CU = carbon associated with unstable aggregates, CNF = carbon associated with net flux, CG = carbon associated with gains, Cx = carbon associated with new stable macroaggregates, Cy = carbon associated with new unstable macroaggregates, Ca = carbon associated with stable macroaggregates that remain stable, and Cb = carbon associated with stable macroaggregates that become unstable, TCFN = total C associated with net flux. n = reference state, and n+l = new state.

<table>
<thead>
<tr>
<th>Index</th>
<th>Conditional</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD&lt;sub&gt;n&lt;/sub&gt; = CD&lt;sub&gt;ARC&lt;/sub&gt;</td>
<td></td>
<td>CD&lt;sub&gt;ARC&lt;/sub&gt; = CU&lt;sub&gt;1,n&lt;/sub&gt; + CU&lt;sub&gt;2,n&lt;/sub&gt;</td>
</tr>
<tr>
<td>CD&lt;sub&gt;n+1&lt;/sub&gt; = CD&lt;sub&gt;SGF&lt;/sub&gt;</td>
<td></td>
<td>CD&lt;sub&gt;SGF&lt;/sub&gt; = CU&lt;sub&gt;1,n+1&lt;/sub&gt; + CU&lt;sub&gt;2,n+1&lt;/sub&gt;</td>
</tr>
<tr>
<td>CFS&lt;sub&gt;1&lt;/sub&gt;</td>
<td>CNF&lt;sub&gt;1&lt;/sub&gt; ≥ 0, Cx&lt;sub&gt;1&lt;/sub&gt; ≥ 0</td>
<td>CFS&lt;sub&gt;1&lt;/sub&gt; = Cx&lt;sub&gt;1&lt;/sub&gt; / CNF&lt;sub&gt;1&lt;/sub&gt;</td>
</tr>
<tr>
<td>CFU&lt;sub&gt;1&lt;/sub&gt;</td>
<td>CNF&lt;sub&gt;1&lt;/sub&gt; ≥ 0, AC&lt;sub&gt;y&lt;/sub&gt; ≥ 0</td>
<td>CFU&lt;sub&gt;1&lt;/sub&gt; = Cy&lt;sub&gt;1&lt;/sub&gt; / CNF&lt;sub&gt;1&lt;/sub&gt;</td>
</tr>
<tr>
<td>CFS&lt;sub&gt;2&lt;/sub&gt;</td>
<td>(CG&lt;sub&gt;2,n&lt;/sub&gt; + CNF&lt;sub&gt;2&lt;/sub&gt;) &gt; 0, Cx&lt;sub&gt;2&lt;/sub&gt; ≥ 0</td>
<td>CFS&lt;sub&gt;2&lt;/sub&gt; = Cy&lt;sub&gt;2&lt;/sub&gt; / (CG&lt;sub&gt;2&lt;/sub&gt; + CNF&lt;sub&gt;2&lt;/sub&gt;)</td>
</tr>
<tr>
<td>CFU&lt;sub&gt;2&lt;/sub&gt;</td>
<td>(CG&lt;sub&gt;2,n&lt;/sub&gt; + CNF&lt;sub&gt;2&lt;/sub&gt;) &gt; 0, Cy&lt;sub&gt;2&lt;/sub&gt; ≥ 0</td>
<td>CFU&lt;sub&gt;2&lt;/sub&gt; = Cy&lt;sub&gt;2&lt;/sub&gt; / (CG&lt;sub&gt;2&lt;/sub&gt; + CNF&lt;sub&gt;2&lt;/sub&gt;)</td>
</tr>
<tr>
<td>CDSM&lt;sub&gt;1&lt;/sub&gt;</td>
<td>CS&lt;sub&gt;1,n&lt;/sub&gt; &gt; 0</td>
<td>CDSM&lt;sub&gt;1&lt;/sub&gt; = Cb&lt;sub&gt;1&lt;/sub&gt; / CS&lt;sub&gt;1,n&lt;/sub&gt;</td>
</tr>
<tr>
<td>CSSM&lt;sub&gt;1&lt;/sub&gt;</td>
<td>CS&lt;sub&gt;1,n&lt;/sub&gt; &gt; 0</td>
<td>CSSM&lt;sub&gt;1&lt;/sub&gt; = Ca&lt;sub&gt;1&lt;/sub&gt; / CS&lt;sub&gt;1,n&lt;/sub&gt;</td>
</tr>
<tr>
<td>CDSM&lt;sub&gt;2&lt;/sub&gt;</td>
<td>CS&lt;sub&gt;2,n&lt;/sub&gt; &gt; 0</td>
<td>CDSM&lt;sub&gt;2&lt;/sub&gt; = Cb&lt;sub&gt;2&lt;/sub&gt; / CS&lt;sub&gt;2,n&lt;/sub&gt;</td>
</tr>
<tr>
<td>CSSM&lt;sub&gt;2&lt;/sub&gt;</td>
<td>CS&lt;sub&gt;2,n&lt;/sub&gt; &gt; 0</td>
<td>CSSM&lt;sub&gt;2&lt;/sub&gt; = Ca&lt;sub&gt;2&lt;/sub&gt; / CS&lt;sub&gt;2,n&lt;/sub&gt;</td>
</tr>
<tr>
<td>CA</td>
<td>CNF&lt;sub&gt;1&lt;/sub&gt; &gt; 0, CNF&lt;sub&gt;2&lt;/sub&gt; &lt; 0, CNF&lt;sub&gt;3&lt;/sub&gt; &lt; 0, CNF&lt;sub&gt;4&lt;/sub&gt; &gt; 0</td>
<td>CA = CNF&lt;sub&gt;1&lt;/sub&gt;</td>
</tr>
<tr>
<td>Cd</td>
<td>CNF&lt;sub&gt;1&lt;/sub&gt; &lt; 0, CNF&lt;sub&gt;2&lt;/sub&gt; &lt; 0, CNF&lt;sub&gt;3&lt;/sub&gt; &lt; 0, CNF&lt;sub&gt;4&lt;/sub&gt; &gt; 0</td>
<td>Cd = 0</td>
</tr>
<tr>
<td>Cα</td>
<td>CNF&lt;sub&gt;2&lt;/sub&gt; &lt; 0</td>
<td>Cα = Cx&lt;sub&gt;2&lt;/sub&gt; + Cy&lt;sub&gt;2&lt;/sub&gt;</td>
</tr>
<tr>
<td>CAD</td>
<td></td>
<td>CAD = [CA + Cα] - [CD&lt;sub&gt;n&lt;/sub&gt; + Cd]</td>
</tr>
</tbody>
</table>
Table 5. The aggregate size-stability distribution under annual row cropped systems and riparian switchgrass filters. Values are pooled data from 1997 and 1998 expressed on a sand-free basis as % of soil aggregates ± 0.1 in each size fraction. Different letters indicate differences (P<0.05) between vegetation treatments within size classes. $TS$ is the total percentage of stable aggregates and $TU$ is the total percentage of unstable aggregates. $T$ is total percentage of soil aggregates $T = TS + TU$.

<table>
<thead>
<tr>
<th>Size fraction $\mu m$</th>
<th>Water pretreatments</th>
<th>Aggregate size-stability distribution (SSD)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Slaked</td>
<td>Capillary-wetted</td>
</tr>
<tr>
<td>REFERENCE STATE</td>
<td>Annual row cropped (ARC)</td>
<td></td>
</tr>
<tr>
<td>&gt; 2000</td>
<td>4.0</td>
<td>33.3</td>
</tr>
<tr>
<td>250 - 2000</td>
<td>43.8</td>
<td>36.5</td>
</tr>
<tr>
<td>53 - 250</td>
<td>24.3</td>
<td>14.2</td>
</tr>
<tr>
<td>&lt; 53</td>
<td>27.9</td>
<td>16.0</td>
</tr>
<tr>
<td>Total</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NEW STATE</td>
<td>Switchgrass filter (SGF)</td>
<td></td>
</tr>
<tr>
<td>&gt; 2000</td>
<td>5.6</td>
<td>38.7</td>
</tr>
<tr>
<td>250 - 2000</td>
<td>41.1</td>
<td>33.9</td>
</tr>
<tr>
<td>53 - 250</td>
<td>30.0</td>
<td>13.2</td>
</tr>
<tr>
<td>&lt; 53</td>
<td>23.3</td>
<td>14.2</td>
</tr>
<tr>
<td>Total</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 6. Amount of organic C associated with each aggregate size fraction under an annual row cropped soil and a riparian switchgrass filter soil. Values are pooled data from 1997 and 1998 expressed in mg C g$^{-1}$ (± 0.1). Different letters indicate differences (P<0.05) between vegetation treatments within size classes. $CTS$ is the amount of carbon associated with stable aggregates and $CTU$ is the amount of carbon associated with unstable aggregates. $CT$ is the amount of carbon associated with soil aggregates $CT = CTS + CTU$.

<table>
<thead>
<tr>
<th>Size fraction (um)</th>
<th>Carbon associated with aggregates after water pretreatments</th>
<th>Carbon associated with aggregates after determination of the size-stability distribution</th>
<th>Slaked</th>
<th>Capillary-wetted</th>
<th>Subsequent-slaked</th>
<th>Stable</th>
<th>Unstable</th>
<th>Gains</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 2000</td>
<td>1.3</td>
<td>7.8</td>
<td>1.3a</td>
<td>6.5a</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>250 - 2000</td>
<td>10.2</td>
<td>8.9</td>
<td>6.0a</td>
<td>6.0a</td>
<td>2.9a</td>
<td>4.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>53 - 250</td>
<td>5.3</td>
<td>2.7</td>
<td>2.7a</td>
<td>2.6a</td>
<td>2.6a</td>
<td>2.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt; 53</td>
<td>4.9</td>
<td>2.4</td>
<td>2.4a</td>
<td>2.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>21.7</td>
<td>21.8</td>
<td>CTS = 12.4a</td>
<td>CTU=9.4</td>
<td>9.3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**REFERENCE STATE**
Annual row cropped (ARC)

**NEW STATE**
Switchgrass filter (SGF)

| > 2000            | 1.5                                                         | 8.2                                                                              | 1.5a   | 6.7a            |                   |        |          |       |
| 250 - 2000        | 11.1                                                        | 9.6                                                                              | 6.3a   | 6.3a            | 3.3a             | 4.8    |          |       |
| 53 - 250          | 5.7                                                         | 2.8                                                                              | 2.8a   | 2.9             |                  |        |          |       |
| < 53              | 5.1                                                         | 2.6                                                                              | 2.6a   | 2.5             |                  |        |          |       |
| Total             | 23.4                                                        | 23.2                                                                              | CTS = 13.2a | CTU=10.0 | 10.2.             |        |          |       |
Table 7. Indicators of soil aggregate dynamics. Values are on pooled data from 1997 and 1998. FIS = formation index of stable macroaggregates. FIU = formation index of unstable macroaggregates. DSM = Index of destabilization of macroaggregates. SSM = Stabilization of stable macroaggregates. $x_2$ = net-change of stable macroaggregates. $y_2$ = net-change of unstable macroaggregates. DI = disruption index. A = represents the amount of aggregates that result for aggregation. d = disruption. ADI = aggregation-disruption index.

<table>
<thead>
<tr>
<th>Size Fraction</th>
<th>$FIS$</th>
<th>$FIU$</th>
<th>$DSM$</th>
<th>$SSM$</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 2000 µm</td>
<td>0.05</td>
<td>0.95</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>250–2000 µm</td>
<td>0.16</td>
<td>0.84</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$x_2$</th>
<th>$y_2$</th>
<th>$DI$</th>
<th>$A$</th>
<th>$d$</th>
<th>$ADI$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARC</td>
<td>44</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SGF</td>
<td>1.8</td>
<td>9.8</td>
<td>43</td>
<td>34.7</td>
<td>0</td>
<td>0.03</td>
</tr>
</tbody>
</table>
Table 8. Indicators for carbon associated with aggregates dynamics pathways. Values are on pooled data from 1997 and 1998. CD = carbon associated with unstable macroaggregates (>250 μm). CFIS = associated Carbon to formation of stable, and CFIU = associated carbon to formation of unstable, CSSM = carbon Associated with Stabilization, and CDSM = carbon associated with destabilization, $C_x$ = carbon associated with new stable macroaggregates, $C_y$ = carbon associated with new unstable macroaggregates, $CAD$ = carbon associated with aggregation and disruption.

<table>
<thead>
<tr>
<th>Size Fraction</th>
<th>$CFS$</th>
<th>$CFU$</th>
<th>$CDSM$</th>
<th>$CSSM$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&gt; 2000 \mu m$</td>
<td>0.03</td>
<td>0.97</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>$250 - 2000 \mu m$</td>
<td>0.09</td>
<td>0.91</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$*C_x^2$</th>
<th>$*C_y^2$</th>
<th>$*CD$</th>
<th>$*CA$</th>
<th>$*Cd$</th>
<th>$*CAD$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARC</td>
<td></td>
<td></td>
<td>9.44</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SGF</td>
<td>0.3</td>
<td>3.3</td>
<td>10.00</td>
<td>6.90</td>
<td>0</td>
<td>1.10</td>
</tr>
</tbody>
</table>

*Values expressed in mg C g$^{-1}$
ASSESSING SOIL QUALITY IN A RIPARIAN BUFFER STRIP SYSTEM BY TESTING ORGANIC MATTER FRACTIONS

A paper accepted by Agroforestry Systems

C.O. Marquez, C.A. Cambardella, R.C. Schultz, and T.M. Isenhart

ABSTRACT

A multispecies riparian buffer strip (MRBS) was established along Bear Creek in central Iowa by the Agroecology Issues Team at Iowa State University (ISU) in order to assess the ability of the MRBS to positively impact soil erosion and process non-point source pollutants in order to improve water quality. Soil organic matter (SOM), and especially biologically-active soil organic matter, is considered to be an important soil quality indicator variable because of its relationship to critical soil functions like erodibility and the capacity of the soil to act as an environmental buffer. The objectives of this study were to examine trends in SOM C accrual and to quantify intra-seasonal changes in SOM C and particulate organic matter (POM) C for each vegetation zone of a MRBS seven years after establishment on previously cultivated or heavily grazed soil. Total SOM C and POM C in soil under perennial vegetation (poplar, switchgrass and cool season grass) were significantly higher than under cropped soil. Total POM C changed within vegetation type over the four month study period, whereas total SOM C did not. After six growing seasons, SOM C increased 8.5% under poplar grown in association with cool season grass, and 8.6% under switchgrass. The results are very promising and suggest that changes in SOM C can occur in a relatively short time after the establishment of perennial vegetation in a MRBS. These changes should increase
the ability of MRBS soil to process non-point source pollutants.

INTRODUCTION

Riparian zones have important geomorphic and hydrologic roles that can support high levels of biological productivity (Van and Jackson, 1990). Although riparian areas may occupy only a small area of a watershed, they represent an extremely important component of the overall landscape (Elmore and Beschta, 1987). Healthy riparian zones may help control transport of sediments and chemicals to stream channels (Lowrance et al, 1984). Most riparian zones have long been negatively influenced by human activities. Numerous approaches have been adopted for mitigating the adverse impacts of agriculture practices within the context of a bioassimilative strategy. These include the restoration of riparian vegetative buffer strips (Osborne and Kovacic, 1993).

In 1990, a multispecies riparian buffer strip (MRBS) was established along Bear Creek in central Iowa by the Agroecology Issues Team at Iowa State University (ISU). The team is supported through the Leopold Center for Sustainable Agriculture, which is located on the university’s main campus in Ames. Bear Creek is typical of many streams in central Iowa where the primary land use of the watershed, including the riparian zone, is row crop production agriculture (corn and soybean) or intensive grazing (Schultz et al., 1995). Five years after establishment of the MRBS along Bear Creek, Schultz et al. (1995) report dramatic alterations in the appearance and function of the riparian buffer strip. After four growing seasons, root biomass increased significantly below the MRBS compared with agricultural crops.
Soil organic matter (SOM) is an important ecosystem component in both natural ecosystems and in intensively-managed agricultural systems (Paul, 1984). SOM is also considered to be an important soil quality indicator variable because of its relationship to critical soil functions like productivity, erodibility and the capacity of the soil to act as an environmental buffer by absorbing or transforming potential pollutants (Sikora and Stott, 1996). Recent research suggests that some of these soil functions may be more directly related to the most biologically-active forms of SOM, and not with the total SOM content (Cambardella and Elliot, 1993).

During the past 20 years, ample evidence has accumulated to demonstrate that physical fractionation of soil provides a significant tool in the study of SOM distribution and dynamics (Christensen, 1992). Physical fractionation techniques are considered chemically less destructive, and the results acquired from analyses of the soil fractions are expected to relate more directly to SOM in situ (Christensen, 1996).

Particulate organic matter (POM) is one example of a biologically-active form of SOM that is isolated using physical fractionation (Cambardella and Elliot, 1992a). Particulate organic matter is considered to be a good indicator of soil quality because it responds rapidly and selectively to changes in land use and soil management (Janzen et al 1992; Cambardella and Elliott, 1992a; Sikora, et al., 1996; Cambardella, 1997).

The objectives of this study were to examine trends in SOM C accrual and to quantify intra-seasonal changes in SOM C and POM C for each vegetation zone of a MRBS seven years after establishment on previously cultivated or heavily grazed soil.
MATERIALS AND METHODS

Field Sampling

Soils were collected from an experimental MRBS that was planted in 1990 along Bear Creek which is located in north central Iowa, within the geological landscape feature called the Des Moines Lobe, a depositional remnant of the Late Wisconsinan glaciation. The basic design of the MRBS consists of three zones of vegetation planted parallel to the stream. The first zone is five rows of trees, grown in association with a cool season grass understory, planted closest to and parallel to the stream at a 1.2 x 1.8 spacing. The trees in this MRBS are *Populus X euramericana* 'Eugenei', a poplar hybrid. The second vegetative zone consists of a row of redosier dogwood (*Cornus stolonifera* Michx.) and a row of ninebark (*Physocarpus opulifolius* L.). The shrubs were planted at a 0.9 x 1.8 m spacing. The third zone is a 7.3 wide strip of switchgrass (*Panicum virgatum* L.) planted upslope from the shrubs at the interface of the cropped field. Controls consist of a cool season grass filter strip that was grazed prior to the study. Dominant grass species in this filter strip are brome grass (*Bromus inermis* Leysser.), timothy (*Phelum pratense* L.) and fescue (*Festuca sp.*).

Both the poplar and the cool season grass filter strips are located on an alluvial floodplain where the dominant soil type is Coland (fine-loamy, mixed, mesic Cumullic Haplaquoll). The switchgrass plots are located on soils that have been cultivated for more than 75 yrs and the soils are mapped as Coland, with some inclusions of Clarion (fine-loamy, mixed, mesic Typic Hapludoll). Soils under soybean (*Glicine max* (L.) *Merr*) are mapped as Clairon.

Soil sampling for the study was conducted along three transects that extended from the stream edge, through the riparian area, toward the riparian zone-agricultural field interface.
(Figure 1). Samples were collected monthly between August and November. Five cores were collected at random from each vegetation per plot per transect with a 2.5-cm-diameter steel coring bit to a depth of 35 cm and composited. The composit, moist soil sample was gently broken by hand, passed through a 2-mm sieve and air-dried. The large pieces of stubble and root that passed through the sieve were removed by hand.

**Laboratory Methods**

A method combining chemical dispersion with particle-size separation was used to isolate POM from air-dried, 2-mm sieved soil taken from each vegetation plot (Cambardella and Elliott 1992b). A 5-g subsample was removed to determine total organic C and a 30-g subsample was dispersed in 100 mL of 5 g L$^{-1}$ sodium metaphosphate and shaken on a reciprocating shaker for 15 h. The dispersed soil sample was passed through a 53-um sieve and rinsed several times with water. The mineral-associated (silt+clay) fraction that passed through the sieve was dried at 70 °C. The mineral-associated fraction and the whole soil samples were ground on a roller mill to pass through a 250 μm.

Total organic C in the whole soil and in the mineral-associated fraction were determined by dry combustion on a Carlo Erba CHN analyzer (Carlo Erba Instruments, Milano, Italy). The amount of C in the POM fraction was calculated as the difference between total soil organic carbon and mineral-associated C.

Differences among treatments were tested by a one-way analysis of variance and linear contrasts with a 0.05 significance level (SAS Institute, 1990).
RESULTS AND DISCUSSION

Total SOM C in perennial vegetation plots (poplar, switchgrass and cool season grass) was significantly higher (≥ 107 Mg ha⁻¹) than in the cropped (≤ 88 Mg ha⁻¹) treatments (Figure 2). Poplar plots had consistently, but not significantly, higher SOM C over the four samples months than cool season grass plots (P≤0.05). No significant differences in SOM C were observed between soils under switchgrass and cool season grass (P≤0.05). Soil organic matter C under switchgrass was significantly lower (107-119 Mg ha⁻¹) than under poplar (151-161Mg ha⁻¹)(Figure 2).

The amount of total SOM C in the perennial vegetation plots in October 1991, one year after establishment of the MRBS, was 123, 141, 104, and 60 Mg ha⁻¹ for soil under cool season grass, poplar, switchgrass, and soybean, respectively (Table 1) (Schultz et al, 1993). After five growing seasons, SOM C in the top of 35 cm of soil increased 8.5% under poplar, 3.2% under cool season grass, 8.6% under switchgrass, and 3.3% under soybean (Table 1). The rate of SOM C sequestration under cool season grass was 0.40 Mg ha⁻¹ yr⁻¹, and under soybeans, 0.12 Mg ha⁻¹ yr⁻¹. The cool season grass and soybean zones have been in place for many years and these systems are likely in equilibrium with respect to SOM C. Soil organic matter C was sequestered at a rate of 2.4 Mg ha⁻¹ yr⁻¹ for the poplar zone and 1.8 Mg ha⁻¹ yr⁻¹ for switchgrass zone. Lal et al. (1997) observed that the rate of SOM C sequestration in the top 20 cm of an Alfisol soil in western Nigeria was 7 to 12 Mg ha⁻¹ yr⁻¹ for Glycine and Melinis grasses, and 1.4 Mg ha⁻¹ yr⁻¹ for Panicum. Fisher et al. (1994 and 1995) observed that grass pastures of Brachiria humidicola alone and grown in association with the legume Arachis pintoi, sequestred 4.1 Mg ha⁻¹ yr⁻¹ and 11.7 Mg ha⁻¹ yr⁻¹,
respectively, over a 6-year period.

Total POM C in soil under perennial vegetation comprised 16-23\% of the total soil C, and was generally higher under poplar than under grass. Perennial vegetation had significantly more POM C than the cultivated systems, where POM C comprised only 9-13 \% of the total soil C, except during October, when it peaked at 15-18\%.

Total POM C changed within vegetation type over the four month study period, whereas total SOM C did not (Fig. 2). Poplar and switchgrass showed a slight, but consistent increase in POM C from August to November. The pattern for cool season grass was less consistent, but POM C was greatest in November compared to the previous three months. Particulate organic matter C for the cropped treatment showed little change except for the October sample date. The peak in October is likely related to increased root inputs as a result of harvest.

Particulate organic matter C is biologically available and a source of C and energy for soil microorganisms. Denitrification has been identified as the predominant soil process for removal of nitrate-N in stream riparian zones (Hill, 1996). The importance of a continuous supply of C to be used as an energy source for sustained nitrate-N removal by denitrifying bacteria suggests that linkages between POM and denitrification are important in riparian zones.

CONCLUSIONS

We have demonstrated that riparian buffer zones have the potential to improve the quality of agricultural soils that have been intensively cultivated. These early results are very promising and suggest that changes in SOM C can occur in a relatively short time after the
reestablishment of perennial vegetation. We may be able to synchronize temporal changes in POM C with temporal changes in denitrification rate, thereby insuring a tight linkage between denitrifying bacteria and the energy source needed to drive denitrification. These changes should increase the ability of MRBS soil to process non-point source pollutants.

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Lal R (1977) Land use and soil management effects on soil organic matter dynamics on


Table 1. Selected chemical and physical characteristics of the surface horizon (0 - 20 cm) of the Coland and Clairon soil series in October 1991 (Schultz, et al., 1993).

<table>
<thead>
<tr>
<th></th>
<th>Coland I</th>
<th>Coland II</th>
<th>Clairon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay (%)</td>
<td>20.0</td>
<td>26.0</td>
<td>15.0</td>
</tr>
<tr>
<td>Sand(%)</td>
<td>43.0</td>
<td>43.0</td>
<td>61.0</td>
</tr>
<tr>
<td>Organic carbon (%)</td>
<td>4.3</td>
<td>3.5</td>
<td>1.7</td>
</tr>
<tr>
<td>PH</td>
<td>7.3</td>
<td>7.0</td>
<td>6.4</td>
</tr>
</tbody>
</table>

Table 2. Changes in carbon content of 0 – 35 cm depth in response to restore a riparian zone.

<table>
<thead>
<tr>
<th>Vegetation Type</th>
<th>Soil C (Mg ha(^{-1}))</th>
<th>Soil C gains</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1991</td>
<td>1996</td>
</tr>
<tr>
<td>Poplar(^a)</td>
<td>141</td>
<td>153</td>
</tr>
<tr>
<td>Cool season grass</td>
<td>123</td>
<td>127</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>104</td>
<td>113</td>
</tr>
<tr>
<td>Crop(^b)</td>
<td>60</td>
<td>62</td>
</tr>
</tbody>
</table>

\(^a\)Poplar is grown in association with cool season grass
\(^b\)Soybean had been in rotation with corn
Figure 1. Temporal changes in POM-C of 0.35 cm for the four vegetation classes in central Iowa, USA. (Each point is the mean three sampling sites, with five samples per site per sampling.)
Figure 2. Plot layout showing the experimental design and vegetation.
Figure 3. Temporal changes in total organic carbon of 35 cm for the four vegetation classes in central Iowa, USA. (Each point is the mean three sampling sites, with five samples per site per sampling.)
GENERAL CONCLUSIONS

We have improved on ability to understand soil stability by developing a theoretical framework that uses a subsequent slaking following the traditionally accepted slaked and capillary-wetted pretreatments to get a more accurate determination of the aggregate size-stability distribution and the amount of stable and unstable macroaggregates in soils under different land-use treatments. Two new indexes, total soil stability index (TSSI) and the soil stability index (SSI), were shown to be highly sensitive to the effects of vegetation on soil stability. The total soil stability index and the soil stability index were higher in soils under cool-season grass filter than under non-buffered annual row crops or 7 yr old switchgrass filter. Soils under cool-season grass were well aggregated with the weighted average of stable aggregates representing 74%, of the dry weight of the soil followed by 55% under existing riparian forest, 38% under switchgrass and 36% under cropped system. The clearest difference between these soils was in the total amount of stable large macroaggregates (>2000μm), which generally differed in the order cool-season grass > existing riparian forest > switchgrass = cropped system. In addition, we developed a new theoretical and conceptual framework for studying soil aggregate dynamics using the soil aggregate dynamics model which integrates aggregation, disruption, stabilization and destabilization of soil aggregates. The model uses the aggregate size-stability distributions associated with two states of the system, the reference and a new state. The new state may be either a degrading or an aggrading system in relation to reference site. A number of convenient indicators are developed to assess aggregation, disruption, stabilization and destabilization of soil aggregates. The predominant process driving the system from the
reference state to the new state is identified and quantified through the aggregation-disruption index (ADI).

Using the size-stability distribution and the soil aggregate dynamics model we were able to assess soil degradation after conversion of a long established riparian cool-season grass filter to cropped system. Soils under cool-season grass have significantly higher amounts of soil aggregates present as stable macroaggregates (53%) compared to cropped system (26%). Results showed that the net process that leads to the new state, cropped system is disruption, which results in the disruption of 19% of the aggregates. In addition, 84% of stable large macroaggregates and 22% of stable small macroaggregates are destabilized. This disruption of macroaggregates exposes previously protected labile organic carbon to decomposers, resulting in a loss of 11.3 mg C g\(^{-1}\) and further destabilization of macroaggregates.

Preservation of a long established riparian cool-season grass filter is important to maintaining the functioning of soil. In fact, CSG plays an important role in the formation and stabilization of aggregates, which in turn protect and temporarily sequestered 11.3 mg C g\(^{-1}\) that has a profound influence on the supply of nutrients, storage of water, release of greenhouse gases, modification of pollutants, resist physical degradation and maintenance of sustainable ecosystems.

In addition, the soil aggregate dynamics model was used to monitor soil aggradation after conversion of agricultural production to riparian switchgrass filters. The results indicate that seven years after the restoration of a switchgrass, the net predominant process is aggregation that results in the formation of 3% of new macroaggregates. Newly formed macroaggregates are mainly unstable. In addition, our results indicate that there is 1.1 mg C g\(^{-1}\) of carbon associated with the 3% of new macroaggregates. None of the previous stable large and small
macroaggregates, presents under the cropped system were destabilized by the conversion of the cropped system to switchgrass. This is one of the important and beneficial points to be highlighted in restoration of grass filter systems. In our study the destabilization of stable macroaggregates that occurs under continuous cropped systems has been stopped mainly due to the introduction of perennial switchgrass.

The relative instability of the newly-formed macroaggregates suggests that chemical composition of the light particulate organic matter and the inputs of light and heavy particulate organic matter play an important role in stabilizing macroaggregates. Indeed, the lower rate of decomposition observed under switchgrass suggests that the presence of lignin which is resistant to decomposition plays an important role in the chemical composition of the light particulate organic matter-C under switchgrass.

In our study, the storage of soil organic C under switchgrass during seven years following establishment occurs at a rate of ~43 g m^{-2} yr^{-1}. This storage rate is comparable with the rate of carbon storage reported by (Franzluebbers, et al. 2000) for C4 grasses during a time period of 10 years but lower compared with the rate of storage under C3 grasses (~100 g m^{-2} yr^{-1})

The amount of total, light and heavy particulate organic matter was not significantly different under switchgrass seven years after establishment than under the cropped system. Our study indicates that the presence of: (i) coarse roots, (ii) higher C/N ratios in the light particulate organic matter, (iii) lower inputs of total particulate organic matter, and (iv) no changes in the alkyl-C/O-alkyl-C carbon ratio over time. These observations supports the hypothesis that switchgrass favors slow carbon sequestration, which in turn hinders the formation of stable macroaggregates in soil in the short term and jeopardizes the overall effectiveness of switchgrass to remove chemicals in a filter system in the short term.
However, the ability of switchgrass to slow surface runoff and trap sediment and its ability to provide wildlife habitat provide positive advantages over the short term.

Under perennial vegetation organic C was stored predominantly in macroaggregates. This is extremely important because organic carbon plays an important role in aggregate development and provides a source of energy for microbial activity. Organic carbon was greatest in the large macroaggregates. The results show that cool season grass has the highest aggregate stability followed by natural forest, switchgrass filters and row crops. This suggests that cool season grass represents an important mechanism for protection and maintenance of soil organic carbon. After 7 year growing season, switchgrass showed less large and small macroaggregates and also lower amounts of carbon associated with aggregates than cool season grass. These results suggest that different mechanisms influence aggregate formation under switchgrass and may be related with: 1) coarse roots system; 2) longer lived roots that are more resistant to decay; 3) lower biomass-C; and 4) lower particulate organic matter. All of these factors together do not support the hypothesis that switchgrass can stimulate the formation of stable large macroaggregates and sequester carbon in short term.

In a degrading system like row crops all the large macroaggregates were very unstable and disrupted. The disruption of these aggregates exposes the previously but relatively labile organic carbon to decomposition, resulting in a loss of soil organic carbon and further destabilization of aggregates.

These results are very promising and suggest that the type of vegetation that you select in to restorer riparian zones that have been degraded are very important because they play an important role in the amount and quality of organic matter that will be incorporated in the
soil, which directly influences the stability, formation of aggregates and storage of organic carbon. Establishing riparian buffers with the proper mix of plant species will influence the formation of large macroaggregates, which will have the potential to sequestrate more carbon with the end result, that infiltration rates increased, surface runoff will be reduced and the source of energy for microbial activity will be increased.