Effects of Conversion to Management Intensive Grazing on Soil Quality

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Abstract

Over the last two decades, increasing concern for environmental protection, as well as quality of life for themselves and their animals, has led some livestock owners to move away from confinement operations to management intensive grazing (MIG). MIG ensures sufficient monitoring and control over animal health, development, and the utilization of resources. Grazing pressure can be controlled through the number of animals allowed to graze an area, and timing can be adjusted to keep animals out of vulnerable areas such as wet or erodible ground during critical periods.

In an attempt to compare benefits of management intensive grazing versus continuous grazing and row crop management, this project sought to determine the impacts of these three management systems on soil quality parameters. Physical, chemical, and biological indicators of soil quality were measured and compared statistically over an eight-year period. Results indicate that most biological indicators of soil quality are better in MIG and CG systems compared to RC. Physical indicators of soil quality indicated that RC management has poorer aggregation, but MIG can result in high bulk densities and penetration resistance. Comparison of chemical indicators of soil quality under the three management systems did not produce definitive results.

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Chapter 1: Literature Review

Introduction

Landscapes around the world have evolved under the influences of animal grazing (Milchunas and Lauenroth, 1993). Grazing by a wide variety of animal species has impacted plant communities, soil biological, physical, and chemical properties, and ecosystems in general (Milchunas et al., 1988). Equilibria have been established between the pressures of grazing, fire, and other disturbance and the productivity of plant communities (Johnson and Matchett, 2001). As people abandoned nomadic ways of life in favor of permanent settlements, free-range grazing by wild and domestic animals was curtailed (Knapp et al., 1999, Mack and Thompson, 1982). People claimed ownership over the land, put up fences, and turned to agriculture to raise crops for food and for profit (Doran et al., 1996). People also domesticated animals and began raising livestock. Though grazing was never eliminated, it became more common for farmers to bring the food to the livestock, rather than allow animals to roam freely (Mack and Thompson, 1982). The purpose of this literature review is to describe the effects of different livestock management practices on soil quality.

Soil as an Indicator of Environmental Health

Since there is no single property that can be universally used to measure the overall "health" of an ecosystem, researchers have analyzed certain components that are thought to have far-reaching impacts on ecosystem sustainability. One key attribute of ecosystem health is soil quality. Doran et al. (1996) defined soil quality as the "capacity of a soil to function, within ecosystem and land use boundaries, to sustain biological productivity, maintain environmental quality, and promote plant, animal and human health". As defined, soil quality cannot be directly measured, but many components taken together can be used to develop a relative evaluation (Acton and Gregorich, 1995). Some of the important indicators of soil quality are organic matter content, carbon and nitrogen content and ratio, pH, cation exchange capacity, soil texture, microbial activity, aggregate stability, water-holding capacity, bulk density, and penetration resistance (Acton and Gregorich, 1995, Doran et al., 1996).

To varying degrees, many soil quality indicators are tied to organic matter content. Organic matter, which can be measured directly by combustion analysis or estimated by chemical oxidation or measurement of cation exchange capacity (Nelson and Sommers, 1996, Krzic et al., 2001), is vitally important for controlling water and nutrient cycling in soils, and for maintaining soil's physical structure (Arevalo et al., 1998, Dalal and Mayer, 1986b, Dormaar et al., 1977, Dormaar and Willms, 1990, Doran et al., 1996, Manley et al., 1995, McBride, 1994, Naeth et al., 1990). Various pools of soil organic matter have been measured in an attempt to quantify active, stable and recalcitrant fractions and to identify trends over time. Light-fraction organic matter (Dalal and Mayer, 1986d, Six et al., 1999), microbial biomass (Banerjee et al., 2000, Dalal and Mayer, 1987b), and aggregate-protected organic matter (Beare et al., 1994) are some of the commonly investigated pools.

The supply and location of many nutrients within the soil is closely tied to organic matter. Organic matter provides binding sites for exchangeable cations (Doran et al., 1996, McBride, 1994) and can be stabilized and protected in soil aggregates (Beare et al., 1994). Nutrient retention, CEC, and mineralization of micro- and macronutrients are directly influenced by organic matter in conjunction with the clay-sized fraction of soils (Doran et al., 1996, McBride, 1994). Furthermore, several investigators have shown that soils low in organic matter are more vulnerable to structural degradation than their OM-rich counterparts (Acton and Gregorich, 1995**,** Manley, et al., 1995). Microbial biomass carbon and biomass activity are closely correlated with soil moisture content (Banerjee et al., 2000, Milchunas and Lauenroth, 1993), which is often highly associated with organic matter (Dick, 1992, Doran et al., 1996). Research has also shown that cultivation of grassland has reduced overall organic matter content (Dalal and Mayer, 1986b, 1987b**,** Dick, 1992, Frank et al., 1995), diminished aggregation (Dick, 1992, Six et al., 1999), and redistributed organically-bound carbon and nitrogen to smaller size fractions within the soil (Dalal and Mayer, 1986c, 1986e, 1987a, Six et al., 1999). Such physical disruption tends to affect the cycling of nutrients in two ways. Initially, decomposition and mineralization of organic matter increase as physical protection of organic matter within macro-aggregates is reduced. As organic matter breaks down, physical protection in micro-aggregates and electrostatic bonding to clay particles increase, making organic matter molecules less available for chemical and biological uptake and reaction. Dick (1992) and Dormaar et al. (1997), among others, have also concluded that application of agricultural chemicals tends to suppress production of enzymes and activity of soil microorganisms that are normally involved in nutrient cycling.

Cropping Effects on Soil Quality

Long-term agricultural management practices have striking effects on a variety of soil quality parameters when compared to natural ecosystems. Dalal and Mayer (1986a) found that organic matter, as indicated by total organic carbon, light-fraction organic carbon, total nitrogen, and mineralizable nitrogen, decreased by 19-67% after 20-70 years of cultivation in a variety of weathered Australian soils. Six et al. (1999) found a 45% reduction in light-fraction carbon in cultivated systems compared to native vegetation. And Banerjee et al. (2000) found that on silty clay loams and clay loams common in central Manitoba, Canada, microbial biomass carbon under grassland ranged from 902-1485 mg/g soil as opposed to 62-795 mg/g soil when cropped. Investigators have also shown varying impacts of cropping on essential nutrients such as inorganic phosphorus, total and exchangeable potassium, total sulfur, and exchangeable manganese and sodium (Dalal and Mayer, 1986a), as well as C/N ratio (Dalal and Mayer, 1986a, 1986e, 1987a). Dormaar and Willms (1990) have shown that soil quality changes can become apparent within as little as four years of initial tillage.

Environmental Impacts of Livestock Confinement

The practice of keeping large numbers of animals in small areas is often called livestock confinement (Fajardo et al., 2001, Koelsch and Lesoing, 1999). Such operations generally require less land than grazing operations, as feed can be brought in from off-farm sources. It is also somewhat more convenient, as the producer has better access to monitor and manage livestock health, diet, and production.

Concentrating large numbers of animals in small areas can have negative impacts on both the animals and the environment. Densely stocked animals have heightened susceptibility to the spread of diseases and parasites (Bicknell et al., 1999), and animal feedlots, waste storage, and disposal areas are widely known to contribute excessive levels of nitrate and phosphorus to the environment (Fajardo et al., 2001, Koelsch and Lesoing, 1999). Confinement systems are generally managed in an attempt to isolate the most severe environmental damage to areas where livestock are housed, fed, or milked. However, concentrations of waste material can lead to contamination of soil, groundwater, and surface waters by chemical constituents or coliform bacteria such as *Escherichia coli* (E. coli) (Fajardo et al., 2001, Koelsch and Lesoing, 1999). Manure application as crop fertilizer has also been shown to lead to surface and groundwater contamination over time, as nutrient levels may eventually reach pollutant status (Fajardo et al., 2001, Koelsch and Lesoing, 1999).

Excessive trampling and vegetation removal by livestock in holding pens and feedlots can have a variety of undesirable effects. Foremost among them are destruction of soil structure and removal of organic material from the soil system (Acton and Gregorich, 1995). Naeth et al. (1990) and other researchers have linked soil compaction and nitrate and phosphorus contamination to dense animal stocking. The explanation for the phenomenon is as follows: Excessive trampling and random grazing removes much of the aboveground plant biomass, which reduces litter on the soil and root activity below ground. Thus, less organic matter is recycled, there is less protective cushioning for the soil, and susceptibility to compaction increases. High phosphorus and nitrate levels may also ensue because there is less plant biomass remaining to take advantage of the nutrients deposited in animal waste. These forms of environmental damage can be exceedingly harmful and widespread in their impact.

Patterns of livestock containment and increased production have continued to the present, but some producers are seeking alternatives to conventional agricultural practices. In an effort to become more "connected" to the land, provide better quality of life for their herds and their families, and recoup premium prices for free range or organic dairy and beef, producers have become more interested in controlled grazing (Acton and Gregorich, 1995). This represents a paradigm-shift away from what might be called the "corporate model" of farming, in which the land is viewed as little more than capital equipment (Doran et al., 1996). The balance of this literature review is an effort to summarize the findings of researchers who have studied the impacts of managed livestock grazing around the world.

Grazing Systems

The two most common managed grazing systems employ rotational or continuous stocking. As the term suggests, in continuous grazing, animals are given season-long, or in some cases, year-round access to rangeland. In rotational grazing, livestock are moved through a series of enclosures, pastures, or paddocks (Arevalo et al., 1998, Dormaar and Willms, 1990, Dormaar et al., 1997, Frank et al., 1995, Manley et al., 1995, Naeth et al., 1990). Successful continuous grazing relies on the balance of stocking rates versus pasture productivity to ensure efficient use of resources. Rotational grazing affords the producer more control, as he or she can manage the degree of defoliation and other impacts by adjusting the amount of time the animals are allowed to graze a given area. Grazing pressure is usually classified as light—20% utilization of annual aboveground biomass production, moderate—50% utilization, heavy—70% utilization, or very heavy—90% utilization (Johnston et al., 1971, Krzic et al., 2001, Manley et al., 1995).

The main control mechanism in continuous grazing is stocking rate, or the number of animals (or animal units, AU) per unit area. As shown in Table 1, stocking rate can be expressed in several ways. In all cases listed, the goal of the system was to provide sufficient high quality forage for livestock to be healthy and productive, while maintaining forage quality for the long-term. Periods of grazing and recovery are generally chosen based on the degree of defoliation and productivity of the plant community.

Table 1. Expression of Stocking Rate

Source	Units	System	Stocking Rate	Duration	Animal
Arevalo et al. (1998)	animals/ha	Rotational	2.3-3.3 animals/ha	9-14 days	cattle
Frank et al. (1995)	ha/steer	Continuous	"moderate"=2.6 ha/steer "heavy"=0.9 ha/steer	season-long	cattle
Hart et al. (1988)	steer-days/ha	Rotational and Continuous	"moderate"=0.33 steer-days/ha "heavy"=0.44 steer-days/ha	varied/ season-long	cattle
Hartnett et al. (1998)	ha/animal unit	Continuous	5-9 ha/animal unit	season-long	bison
Johnston et al. (1971)	ha/animal unit month	Continuous	"light"=0.8 ha/AUM, to "very heavy"=0.2 ha/AUM	season-long	cows and calves
Manley et al. (1995)	steer-days/ha	Rotational and Continuous	"light"=22 steer-days/ha "heavy"=67 steer-days/ha	varied/ season-long	cattle

Both rotational and continuous grazing systems may mimic evolutionary grazing activity (Fuhlendorf and Engle, 2001). Rotational grazing includes periods of rest and recovery for plants between grazing events. During those periods, solid and liquid waste from the animals is broken down and nutrients can be cycled by plants and microbes (Brockway et al., 2002, Johnson and Matchett, 2001, Steinauer and Collins, 2001). The patchy nature of the waste application leads to growth advantages for certain plants and communities of soil organisms, which in turn results in uneven ground-cover that diversifies the landscape and promotes species richness (Brockway et al., 2002, Hartnett et al., 1998). Under appropriate stocking rates, continuous grazing may also resemble evolutionary grazing, but without guaranteed periods of rest and recovery. In such cases, the producer relies upon the patchy nature of grazing activity and waste deposition to spread grazing pressure over the entire available area (Steinauer and Collins, 2001, Stohlgren et al., 1999). Small pockets of regeneration and enrichment must maintain the diversity and health of the overall ecosystem (Hartnett et al., 1998, Stohlgren et al., 1999).

Both systems tend to benefit soil quality and plant vitality by recycling carbon and nitrogen in forms that are readily available for plants and soil microorganisms (Brockway et al., 2002**,** Steinauer and Collins, 2001). Decomposition of plant material is generally slow in arid and semi-arid grasslands, and may prove to be the rate-limiting step for nutrient cycling in those environments (Brockway et al., 2002). In humid, temperate regions, water and nitrogen supplies are rate-limiting (Whitehead, 2000). Deposition and breakdown of animal waste speeds the process, but is still slow in comparison to the nutrient turnover caused by fire in native rangeland ecosystems (Brockway et al., 2002, Johnson and Matchett, 2001).

Grazing of pasture lands has widely varied impacts on soil quality and plant communities. Rotational grazing can improve forage quality over continuous grazing (Banerjee et al., 2000). In other studies, Dormaar et al. (1997) and Milchunas and Lauenroth (1993) found that rotational grazing could improve forage quality and aboveground net primary productivity over levels found under zero-grazing systems.

Increased plant vigor in response to grazing has been credited for such findings (Dormaar et al., 1997, Manley et al., 1995). Milchunas and Lauenroth (1993) also showed that under some conditions, insufficient grazing can lead to excessive litter accumulation, which can hinder seed germination and seedling development, while Johnston (1971) found that excessive grazing can lead to erosion and desertification. Other studies have shown that soil bulk density increases with grazing intensity, and that very heavy grazing can lead to conditions consistent with a drier microclimate (Dormaar et al., 1977, Naeth et al., 1990). Naeth et al. (1990) explained the hazards of excessive stocking by citing extreme soil compaction, defoliation, nutrient contamination of the environment, and subsequent ecological upheaval as potential outcomes.

Soil organic carbon has been found to be lower in moderately grazed pastures than either exclosures or under heavy grazing (Frank et al., 1995). Several investigators, including Arevalo et al. (1998), Dormaar et al. (1977), and Manley et al. (1995), have referred to a “fragile equilibrium” in the environment. They describe situations in which, if there are low native organic matter levels, there is little resistance on the part of the soil to biological, chemical, or physical change. If managed carefully, the type of grazing system (rotational or continuous) generally does not impact soil quality, but the degree of grazing pressure from either system can have serious impacts (Banerjee et al., 2000, Johnston et al., 1971, Milchunas and Lauenroth, 1993, Naeth et al., 1990).

Grazing Effects on Soil Organic Matter

Soil organic matter and the nutrients associated with it are key components of sustainable grazing systems (Doran et al., 1996). Soil organic carbon in grasslands can be thought of as the balance between inputs from root and microbial turnover, manure and urine deposition, and plant residues left on the surface with losses to mineralization, sequestration, animal uptake, fire, and erosion. Many studies have indicated that carbon levels may be elevated under some grazing regimes (Arevalo et al., 1998, Banerjee et al., 2000, Dormaar et al., 1977 and 1984, Dormaar and Willms, 1990, Frank et al., 1995, Krzic et al., 2001, Manley et al., 1995). Such findings lend support to the statement that responsible grazing can benefit the soil, and therefore, the rangeland ecosystem. The intensity of grazing activity is of primary importance, as under some circumstances, heavy grazing actually appears to out-perform moderate grazing, or even total protection from grazing, in terms of soil chemical impacts (Dormaar et al., 1997, Frank et al., 1995). However, positive reports of heavy grazing should be carefully evaluated, as it is possible that certain lag effects of environmental response can over-ride the actual effects of any grazing system (Dick, 1992). Soils with inherently high fertility and water-holding capacity buffer against expected environmental change (Stohlgren et al., 1999). It is also possible that seasonal (Banerjee et al., 2000, Dormaar et al., 1977), environmental (Friesen et al., 1985), or climatic (Milchunas and Lauenroth, 1993) variation may serve to obscure the impacts of management strategies. Also, as Hierarchy Theory (Milchunas and Lauenroth, 1993) dictates, observations at one level of a system may not be indicative of responses at another level.

Soil microbes can also be affected by livestock grazing. As mentioned earlier, the microbial component of soil organic matter is a key indicator of the status of an ecosystem (Banerjee et al., 2000). As plant communities undergo changes, associated shifts in the soil biota also occur. Together, plants and microorganisms combine to produce enzymes as part of their metabolic processes. Changes in microbial community structure are difficult to quantify, but potentially vital because the soil biota drives nutrient and energy transformation in the soil (Banerjee et al., 2000).

Grazing Effects on Soil Physical Parameters

Soil compaction is an important consideration for grazing operators. Often the result of diminished soil structure combined with mechanical compression of the soil, compaction can have serious and long-lasting effects on soils. Though compacted soils are a common by-product of grazing operations, serious problems are rare if the systems are well-managed. Sound management strategies can prevent setbacks, and in some cases help remedy pre-existing problems (Arevalo et al., 1998, Dormaar and Willms, 1990, Dormaar et al., 1997). Compaction reduces water infiltration, and impairs aeration and root penetration (Krzic et al., 2001). Arevalo et al. (1998) determined the compacting force of adult cattle to be 1.7 kg/cm^2, or roughly equivalent to that of wheeled tillage equipment, and found that the effects on bulk density may reach one meter in depth. Most researchers have found some increase in bulk density and/or penetration resistance after periods of grazing, but it has rarely reached levels that would inhibit root growth (Naeth et al., 1990). Naeth et al. (1990) listed 2000 kilopascals (2.0 Mpa) as a threshold value of penetration resistance that could inhibit root growth, and bulk densities between 1.55 and 1.8 g/cm3 have been shown to restrict root growth in various soil types (Whitehead, 2000). Even under heavy grazing, soil compaction can be limited by removing livestock from at-risk areas during critical periods (Naeth et al., 1990).

By keeping stocking rates at reasonable levels and maintaining a cushioning layer of vegetation, compaction can be kept in check (Arevalo et al., 1998, Naeth et al., 1990). Vegetation limits compaction both by dispersing animal weight across the soil surface, and through root activity helping maintain soil structure and porosity. Soils are most susceptible to compaction during periods of excess soil moisture and reduced plant biomass, such as early spring (Frank et al., 1995, Naeth et al., 1990). Coarse textured soils are generally more susceptible than fine textured ones (Naeth et al., 1990), and high traffic areas like cattle pathways can be severely compacted even at low overall grazing intensity (Naeth et al., 1990).

Bulk density and penetration resistance are the two most common ways to measure soil compaction. Bulk density reports the weight per unit volume of soil, whereas penetration resistance measures mechanical resistance to objects (such as roots) moving through the soil. Penetration resistance is a more sensitive measure of compaction than bulk density (Naeth et al., 1990). However, the concept of bulk density is easily understood and it can be used in interpreting many other measures of soil biological and chemical data. For these reasons, several investigators have used bulk density and penetration resistance in combination to quantify the physical effects of grazing on the soil. Manley et al. (1995) commented on the problems associated with reporting soil C and N as concentrations because that information can be misleading due to elevated bulk densities.

Bulk density can undergo extreme changes under grazing. Krzic et al. (2001) found a 64% increase in bulk density upon grazing of previously forested land. And Banerjee et al. (2000) measured significantly increased bulk density under grazing after just one year. Virtually all studies have shown increased bulk density and penetration resistance following grazing, but with different timing and intensity of response. Such variation illustrates the confounding effects that wet-dry and freeze-thaw cycles, as well as vegetation and soil type all have on physical measurements in soil (Naeth et al., 1990).

One aspect of soil compaction that makes it especially important to grazing management is that it occurs primarily near the soil surface, where plants, soil, atmosphere, and micro- and macro fauna all interact. While penetration resistance and bulk density may be affected to significant depths in some soil profiles (Krzic et al., 2001), changes are usually concentrated in the uppermost portion of the soil. Both measures are generally lowest near the surface in ungrazed grassland (Krzic et al., 2001, Naeth et al., 1990). Therefore, the rooting zone is most susceptible to grazing-induced compaction. Manley et al. (1995) have calculated that 70-90% of all root biomass in grassland is in the top 30 cm of the soil. The presence of forbs in mixed prairies may help to alleviate the effects of compaction because of their deeper root systems (Krzic et al., 2001). However, cattle tend to preferentially graze grasses rather than forbs (Krzic et al., 2001), so the possibility exists of shifting species distribution away from the ideal forage.

Grazing Effects on Forage Quality

Even subtler than species shifts, changes in quality of herbage can be very important for sustaining grazing systems. It is widely known that forage quality varies seasonally in all grazing systems (Banerjee et al., 2000). Numerous studies have shown a decrease in forage quality with grazing (Arevalo et al., 1998, Frank et al., 1995), but others have shown improvements (Banerjee et al., 2000). Most findings of improved feed quality under grazing credited “plant stimulation” for the observed changes (Banerjee et al., 2000, Manley et al., 1995), concluding that grazing stimulates re-growth, and with more fresh plant biomass available, livestock are able to consume a more nutritious mixture of forage.

Plant responses to grazing and other disturbance vary with the physiological characteristics of the species or life form. Rhizomatous plants are generally better adapted to withstand grazing than plants without rhizomes (Pfeiffer and Hartnett, 1995). C3 species often out-compete C4 species when subjected to burning (Steinauer and Collins, 2001), but grazing can help keep them in balance, as grazers tend to select the highest quality forage available at any given time and location (Anderson, 2000). Seasonal effects also contribute to maintaining forage quality. Mixed pastures of cool- and warm-season grasses and legumes can provide high quality forage throughout the growing season.

Adaptive strategies to dealing with grazing can include anything that lessens the likelihood of being eaten (Johnson and Matchett, 2001). Specifically, Milchunas and Lauenroth (1993) listed avoidance mechanisms such as prostrate growth forms or the development of unpalatable tillers in bunchgrasses as examples. Application of nitrogen in livestock urine has been shown to improve plant productivity, and to increase the palatability of plants to livestock, while reducing plant diversity at the application site (Steinauer and Collins, 2001). Seed dispersal through animal waste can also work in concert with grazing pressure to control or change plant species distribution (Stohlgren et al., 1999). Patchy addition of waste can cause nutrient discontinuities within pasture soils (Banerjee et al., 2000, Gerrish et al, 1995). In general, grazing tends to encourage greater plant diversity in arid and semi-arid environments, but often reduces the numbers of locally dominant species (Dormaar et al., 1977, Milchunas and Lauenroth, 1993).

Effects of Grazing History

A final consideration related to the impact of grazing on soil quality is the evolutionary history of grazed lands. Milchunas and Lauenroth (1993) conducted an extensive review of grazing systems around the world and found responses to be closely related to the history of grazing on a given site. In general, it appears that the more prevalent grazing has been in the long-term development of a particular ecosystem, the better that system is able to withstand the pressures of grazing. When investigators (Dormaar et al., 1997 and Manley et al., 1995) claim that their findings indicate an improvement in forage or soil quality under grazing, it is likely that the system was pre-disposed to function well under those conditions. Results similar to those of Johnston et al. (1971), showing poorer soil quality after grazing, may indicate that certain sites are not able to withstand those pressures.

A third set of results, which fail to show any conclusive, consistent, directional response to grazing pressure may illustrate still another point. Mixed effects of grazing, as shown by numerous authors, could be a function of the measurements themselves (Arevalo et al., 1998, Banerjee et al., 2000, Frank et al., 1995, Manley et al., 1995, Milchunas and Lauenroth, 1993, Stohlgren et al., 1999). Friesen et al. (1985) touched on the issue with their concern about the impact of plot and study scale on experimental results. Stohlgren et al. (1999) investigated the problem further and referred to the "intermediate disturbance hypothesis" to describe it. They explained that grazing might impose a level of recurrent disturbance that reduces competition, leaving more resources available for resilient and/or invader species, which could result in greater diversity than in continuously grazed sites.

Conclusion

Managed livestock grazing can impact the ecosystem in a variety of ways. If managed poorly, grazing can damage soil structure and plant communities, which in turn may harm water quality and the overall health of the environment. However, when managed effectively, the defoliation, trampling, selectivity, and animal waste production that result from livestock grazing can maintain, or even improve range and soil quality, and environmental health (Arevalo et al., 1998, Banerjee et al., 2000, Manley et al., 1995, Milchunas and Lauenroth, 1993, Naeth et al., 1990).

Plant species distribution is often controlled more by environmental factors, seed dispersal, availability of water and nutrients, and historic land use than by grazing (Stohlgren et al., 1999). Since no two sites are identical to begin with, and grazing impacts are inherently heterogeneous, it is clear that care must be taken in drawing conclusions from rangeland analyses (Stohlgren et al., 1999). Some plant communities are resilient to grazing and changes in grazing pressure, while others are not (Dormaar et al., 1997). Organic matter dynamics are also tied strongly to seasonal effects and changes in grazing pressure (Dormaar et al., 1977), though often with no predictable or consistent effect (Manley et al., 1995). With so much variability and discontinuity, it is clear that intensive spatial and temporal sampling is needed to accurately quantify the impacts of any grazing system (Friesen et al., 1985).

There appear to be two focal points for evaluating the effect of grazing on rangeland. Soil organic matter content and degradation of soil structure are tied to virtually all the potential impacts of livestock grazing. Variation in microbiological and biochemical properties is not directly dependent on soil organic matter, but is closely related to soil moisture content, which is partially controlled by organic matter (Banerjee et al., 2000). Soil organic matter is vitally important for grazing because it buffers changes in the soil environment, maintaining healthy soil and vegetation status (Manley et al., 1995), and controls the expression of environmental factors such as water content, water holding capacity, temperature regulation, and nutrient cycling (Manley et al., 1995).

Damage to soil structure can often be observed through the compaction of soil (Acton and Gregorich, 1995, Banerjee et al., 2000, Dalal, and Mayer, 1986a, Krzic et al., 2001). When compaction occurs, not only are water and air permeability affected (Acton and Gregorich, 1995, Doran et al., 1996, McBride, 1994), but the expression of other soil parameters can be affected. Since most soil properties are expressed per unit volume of soil, changes in bulk density can greatly affect how soil data and information are communicated and interpreted (Manley et al., 1995).

Caution must be exercised when considering soil data from rangeland, especially since the true native condition of a study site is rarely known (Dormaar et al., 1997). It would be unwise to try to discern the health of an entire system simply from one parameter (Dormaar et al., 1997, Milchunas and Lauenroth, 1993). Since changes in bulk density or root mass distribution may have drastic effects on any or all soil parameters (Dormaar and Willms, 1990), it would be better to use an integrated indicator such as soil quality to evaluate the relative health of the ecosystem (Dormaar et al., 1997). However, one should not consider soil quality independent of other parameters affecting or including vegetation, climate, or long-term management (Dormaar et al., 1997, Milchunas and Lauenroth, 1993).

Based on a review of the literature, it is clear that well-managed grazing systems can maintain or improve soil quality and overall pasture and rangeland sustainability. Responsible grazing management tends to maintain or improve soil physical, biological and chemical condition (Arevalo et al., 1998, Banerjee et al., 2000, Manley et al., 1995, Naeth et al., 1990). Carefully timed grazing events can be a tool for range management, and plant species diversity can be maintained (Milchunas and Lauenroth, 1993, Naeth et al., 1990), ensuring the sustainability of grazing management systems for years to come.

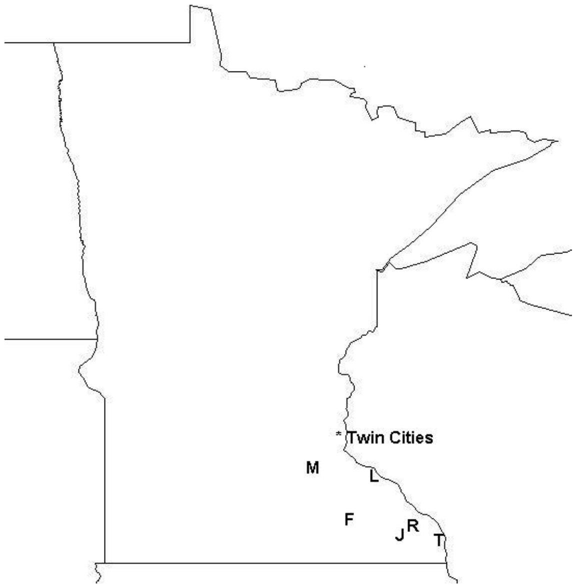
Chapter 2: Effects of Management Intensive Grazing on Soil Quality

Materials and Methods

Site Selection

A group of staff from the Land Stewardship Project, and a number of state and local agencies, as well as several farmers from southeastern Minnesota and researchers from the University of Minnesota organized themselves in 1993 to monitor effects of MIG on a number of biological and social indicators. Sites were identified in order to measure soil quality effects over time under management intensive grazing (MIG). The intention was to use paired measurements (MIG vs. continuous grazing, MIG vs. row crop), for direct comparison of the effects of MIG in relation to other common agricultural land uses. Specific monitoring plot locations were selected based on the interest of the six farmers on the team, with care taken to stay within soil-mapping units and avoid transitional areas. A soil survey specialist was hired to verify soil types at plot locations before any measurements were taken.

FIGURE 1: MN Map with Cooperator Farm Locations



On the farms involved in this study, animals were typically allowed to graze until remaining stubble was 8-15 cm tall. Table 2 contains grazing pressure information for the six farms included in the study.

Table 2. Summary of Grazing Pressure on MIG Plots

Farm F	4-6 Grazing Events/year, 1 day each. Usually 2 additional hay cuttings taken each year.
Farm J	2-4 Grazing Events/year, 4-10 day each. Average 28,000 kg/ha live weight.
Farm L	3-5 Grazing Events/year, 3-6 day each. Average 11,200 kg/ha live weight.
Farm M	3-8 Grazing Events/year, 1-2 day each. Usually 1 additional hay cutting taken each year.
Farm R	2-8 Grazing Events/year, 1 day each. Average 67,000-73,000 kg/ha live weight.
Farm T	4-6 Grazing Events/year, 1 day each. Average 67,000-73,000 kg/ha live weight.

At the beginning of the project, five of the six farms had suitable row crop areas for the MIG vs. RC comparison, and four of the six had permanent pastures (for MIG vs. CG comparison) (Table 3). There were 53 plots established for the initial sampling, in spring 1994. The varied management histories are summarized in Appendix A.

Table 3. Plot Counts

Number of Plots Sampled each Fall				
MGMT	**1994**	**1995**	**1996**	**2002**
Management Intensive Grazing	43	43	42	22
Row Crop	8	7	7	4
Continuous Grazing	5	4	4	3
Total	56	54	53	29

Plot Location

Prior to sampling in the spring of 1994, plots were positioned, mapped and measured in relation to "permanent" landmarks. The plots were laid out as 5*5 meter squares, oriented North-South by compass readings. Steps were taken to minimize the chance of sampling any single location repeatedly. Each plot was marked at the corners with wooden stakes. All stakes were removed from row-cropped areas after sampling to prevent damage to farm equipment. In 1997, GPS was used to record latitude and longitude coordinates for most of the plots.

Plots were grouped by "factors" (drainage, landscape position, and soil texture) and divided into categories for analysis (Appendix A). Drainage was classified as well, poor, or moderate, as a simplification of USDA-NRCS Drainage Classification system. Well or excessively drained soils were classified as "well". Moderately well drained and somewhat poorly drained soils were classified as "moderate". Poorly and very poorly drained soils were classified as "poor". A plot's position within the local landscape was used to classify it as "top", "middle", or "bottom". This classification was largely based on observation and judgment, with the three levels generally corresponding to eroding surface, no net loss, and accumulating position, respectively. Six textural classes from the USDA-NRCS Soil Texture Classification system were present within the 60 sample locations. The classes present were identified as clay, clay loam, loam, silt loam, silty clay, and silty clay loam.

The majority of plots in this study were on 0-4% slopes of varying shape. Soils were fertile and not highly developed. Most were classified as Hapludalfs, Argiudolls, or Endoaquolls.

Field Data Collection and Soil Sampling

Field sampling of soils was conducted according to the schedule in Table 4. Soil core samples were collected by hand from within the plots, and were used for biological, chemical, and physical analyses. Bulk samples for aggregate stability analysis were collected from randomly selected positions immediately adjacent to the plots to minimize disturbance within the plots.

Table 4. Schedule of Sampling Activity

Biological	Spring '94	Fall '94	Spring '95	Fall '95	Spring '96	Fall '96	Fall '02
Microbial Biomass Carbon	X	X	X	X	X	X	X
Microbial Biomass Nitrogen	X	X	X	X	X	X	X
Respiration	X	X	X	X	X	X	X
Soil Moisture Content	X	X	X	X	X	X	X
Chemical							
Total C and N	X	X		X		X	X
Organic Matter Content	X	X		X		X	X
Particulate Organic Matter					X	X	X
Cation Exchange Capacity	X	X		X		X	
pH	X	X		X		X	X
Macronutrients (NPK)	X	X		X		X	X
Physical							
Particle Size Analysis						X	
Bulk Density	X	X		X		X	X
Cone Index		X					X
Aggregate Stability	X	X	X	X	X	X	X
Soil Moisture Content	X	X	X	X	X	X	X

Measurement of Soil Biological and Chemical Properties

In most soils in the upper Midwestern United States, organic matter comprises 1 to 5% of the total soil mass. However, difficulties in direct measurement of organic matter make it more practical to report organic carbon content as an index of organic matter (Nelson and Summers, 1996). Direct measurement of organic matter content was conducted directly by loss on ignition (LOI) as described by Schulte (1988). Soil total carbon and nitrogen were also measured by dry combustion using a LECO CN-2000 (LECO Corp., St Joseph, MI).

Particulate organic matter (POM) is defined as organic matter ranging in size from 53-2000 μm (Cambardella and Elliot, 1992). POM carbon and nitrogen were measured in an effort to quantify more labile pools of organic matter (Wander and Bollero, 1999). Soil samples were sieved to 2 mm, chemically dispersed with a solution of 10% (weight/volume) sodium metaphosphate in water, and separated by washing through polyester cloth with a pore size of 53 μm. Samples consisting of POM and sand were ball-milled to a powdery consistency and analyzed in the same fashion as the total C/N samples.

To minimize the variability in microbial biomass carbon and nitrogen, core samples were collected in fall each year (mid-September through late October), after plant growth had largely ceased and microbial activity was expected to have stabilized. Cores from the 0-8 cm depth were sieved to 2 mm to remove stones and intact plant material, and kept cool and field-moist until processing. Microbial biomass carbon, nitrogen, and respiration rate were determined using a modification of the fumigation procedures described by Jenkinson and Powlson (1976), and Vance et al. (1987) (Appendix B).

Soil core samples collected from each plot were analyzed for chemical composition several times throughout the course of the study, following the schedule shown in Table 4. Samples were sieved to 2 mm to remove rocks and large pieces of organic matter, and then air dried for analysis. Standard soil chemical tests for pH, Bray I-extractable phosphorus, and ammonium acetate extractable potassium were performed.

Soil water content measurements were obtained from subsamples of the soil microbial biomass cores and bulk aggregate stability samples, and from the intact bulk density cores. Water content was determined gravimetrically using the technique described by Gardner (1986).

Measurement of Soil Physical Properties

Bulk density was measured with the procedure described by Allmaras et al. (1988). Cores collected with a specially-designed tube sampler were divided by depth and placed in separate moisture tins. For the initial sampling, samples were divided into 2-cm depth increments. For all subsequent samplings, 5-cm increments were used. Data is presented as composites from the 0-8 and 8-20 cm depths.

Wet aggregate stability was determined using a nested wet sieving technique adapted from Kemper and Chepil (1965). Samples were sieved to 8 mm to remove stones and organic matter and air dried at room temperature. They were then re-wetted at atmospheric pressure via slaking, and shaken for 10 minutes using a shaker similar to that described by Yoder (1936). Material from each of the nested sieves was dried and weighed to determine the amount of water-stable aggregates in each size class. Geometric mean diameter and the weight of aggregates greater than 1 mm in diameter were calculated. GMD is a useful index for reporting data on size class breakdown in a single number, and aggregates greater than 1 mm have particular importance in organic matter dynamics (Aoyama et al., 1999).

Cone index was determined using a Bush Recording Soil Penetrometer (Findlay, Irvine Ltd., Midlothian, Scotland). The unit was programmed to record penetration resistance in megaPascals (MPa) at 2.5 cm intervals to a depth of 30 cm. Due to difficulties in obtaining consistent readings, data was composited across the 0-8 and 8-23 cm depths.

Particle size analysis was conducted after the fall, 1996 sampling. Core samples were sieved to 2 mm and treated to chemically disperse aggregates, oxidize organic matter, and destroy carbonates. After pre-treatment, particle size distribution was determined by the hydrometer method described by Gee and Bauder (1986).

Statistical Analysis

Data were tested for normality using the Shapiro-Wilk test procedure in PROC UNIVARIATE (SAS Institute, 2002). Non-normal distributions were log-transformed to approximate normality. Variables for which normality was improved by log-transformation included TOC, total soil N, microbial respiration rate, MBC, MBN, POM C, POM N, POM NN, Bray P, and ammonium acetate extractable K. Data that required transformation were converted to logarithms for statistical analysis, then back-transformed for reporting. Because the normality of bulk density from the 0-8 and 8-20 cm depths, GMD, Aggregates > 1mm, and soil pH data did not improve with transformation, the untransformed data were used for statistical analysis.

Analysis of variance was performed using PROC Mixed (SAS Institute, 2002) to evaluate management and topographical differences within sampling dates from 1994 through 1996. Means were compared using the PDIFF option of the LSMEANS statement. Two sample t-tests were conducted in the R (version 2.90) Statistical Package (Freeware, available at www.r-proj.org) to determine changes between plot establishment in 1994 and the final sampling in 2002 for most indices, and between 1996 and 2002 in the case of POM measurements.

Results

Management Comparisons, 1994-1996

Because plot numbers were much lower in 2002, management and landscape position comparisons could be undertaken only with data from 1994, 1995, and 1996. There were no differences in total soil carbon among the three management systems in any year, and total N differed only in 1995, when both MIG and continuous grazing had higher levels than row crop plots (Figure 2).

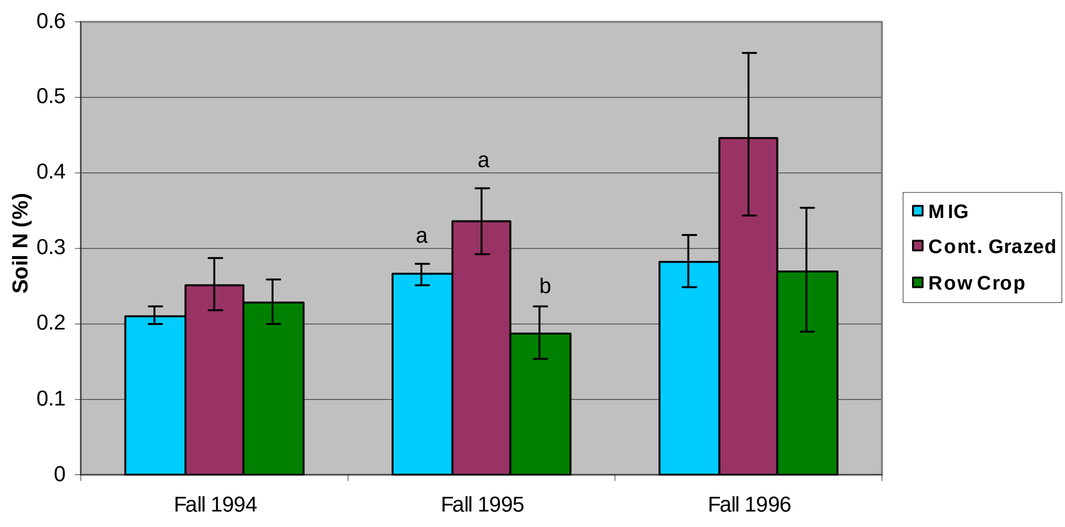
Table 5. Effect of Management on Measures of Soil Organic Matter

	Total Organic Carbon			**Total Soil Nitrogen**		
	Fall 1994	Fall 1995	Fall 1996	Fall 1994	Fall 1995	Fall 1996
Management	**(% C)**	**(% C)**	**(% C)**	**(% N)**	**(% N)**	**(% N)**
MIG	2.40 (2.26, 2.55)*	3.00 (2.83, 3.17)	2.68 (2.53, 2.84)	0.21 (0.20, 0.22)	0.27a (0.25, 0.28)**	0.28 (0.25, 0.32)
CG	2.52 (2.11, 3.01)	3.42 (2.90, 4.04)	2.76 (2.34, 3.25)	0.25 (0.22, 0.29)	0.34a (0.29, 0.38)	0.45 (0.34, 0.56)
RC	2.58 (2.21, 3.00)	2.55 (2.21, 2.94)	2.79 (2.42, 3.21)	0.23 (0.20, 0.26)	0.19b (0.16, 0.22)	0.27 (0.19, 0.35)
MG-RC p-value	ns	ns	ns	ns	0.038	ns
MG-CG p-value	ns	ns	ns	ns	0.125	ns
CG-RC p-value	ns	ns	ns	ns	0.007	ns

*-Values represent mean (mean less one standard deviation, mean plus one standard deviation) after back-transformations of log-transformed statistics.

**-Numbers within a column followed by different letters are significantly different at p< 0.05.

Figure 2. Effect of Management on Total Soil Nitrogen



-Columns represent means (error bars represent mean less one standard deviation, mean plus one standard deviation) after back-transformations of log-transformed statistics.
-Columns marked with different letters within groups are significantly different at p< 0.05.

Landscape position had significant effects on both total carbon and nitrogen in 1994 (Table 6). In 1994, both TOC and Total N were statistically lowest at the top of the landscape and highest at the bottom of the landscape ($p < 0.05$), with mid-slope positions intermediate between the two. In 1996 TOC concentrations were lowest at the upslope positions while the middle and bottom positions were both significantly larger ($p < 0.05$).

Table 6. Effect of Landscape Position on Measures of Soil Organic Matter

	Total Organic Carbon			**Total Soil Nitrogen**		
	Fall 1994	Fall 1995	Fall 1996	Fall 1994	Fall 1995	Fall 1996
Position	**(% C)**	**(% C)**	**(% C)**	**(% N)**	**(% N)**	**(% N)**
Top	1.98a (1.81, 2.17)* **	2.80 (2.57, 3.05)	2.10x (1.93, 2.28)	0.18a (0.17, 0.20)	0.25 (0.22, 0.27)	0.25 (0.20, 0.29)
Middle	2.61ab (2.25, 3.03)	2.86 (2.49, 3.29)	3.14y (2.70, 3.65)	0.24ab (0.21, 0.27)	0.25 (0.22, 0.29)	0.42 (0.33, 0.52)
Bottom	3.02b (2.72, 3.36)	3.26 (2.95, 3.60)	3.13y (2.84, 3.45)	0.27b (0.25, 0.29)	0.29 (0.27, 0.32)	0.33 (0.28, 0.39)
Top-Mid p-value	0.077	ns	0.012	0.068	ns	ns
Top-Bot p-value	0.001	ns	0.001	<0.001	ns	ns
Mid-Bot p-value	0.342	ns	0.973	0.210	ns	ns

*-Values represent mean (mean less one standard deviation, mean plus one standard deviation) after back-transformations of log-transformed statistics.

**-Numbers within a column followed by different letters are significantly different at p< 0.05.

Two primary biological indicators of soil quality, microbial respiration rate and microbial biomass carbon content, were likely affected by ambient temperature and/or moisture content in 1996 (Tables 7 and 8). All three managements displayed higher respiration rate and MBC levels in fall 1996 than at any other time during the study (Figures 3 and 4). Microbial respiration rate and MBC in both grazing treatments was greater than for row crop in each year ($p < 0.05$).

Table 7. Average Air Temperature Prior to Sampling Events (in degrees C)

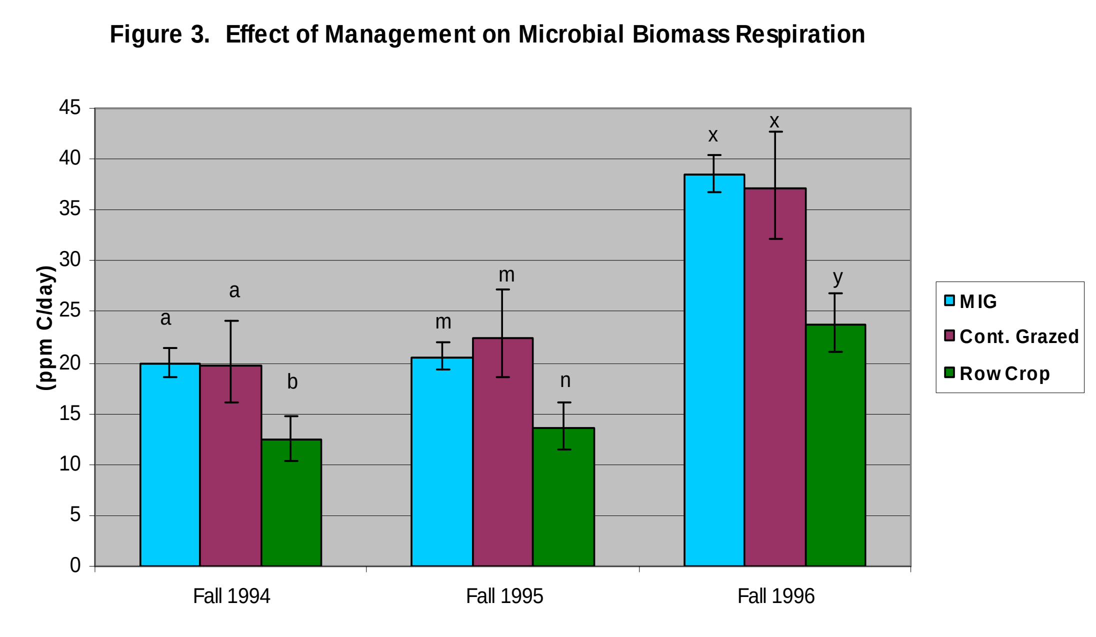
	7-Day Average		Previous 7-Day Avg.		30-Day Average	
Sampling	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**
25-Oct-94	14.8	5.5	19.9	8.3	17.3	7.2
27-Sep-95	15.6	3.3	20.5	6.6	23.1	12.1
30-Sep-96	18.3	6.8	21.2	7.9	23.1	10.3
20-Oct-02	9.4	-0.6	16.3	3.2	15.3	4.3

Temperature data averaged from National Weather Service Cooperative program sites closest to each farm in the study.

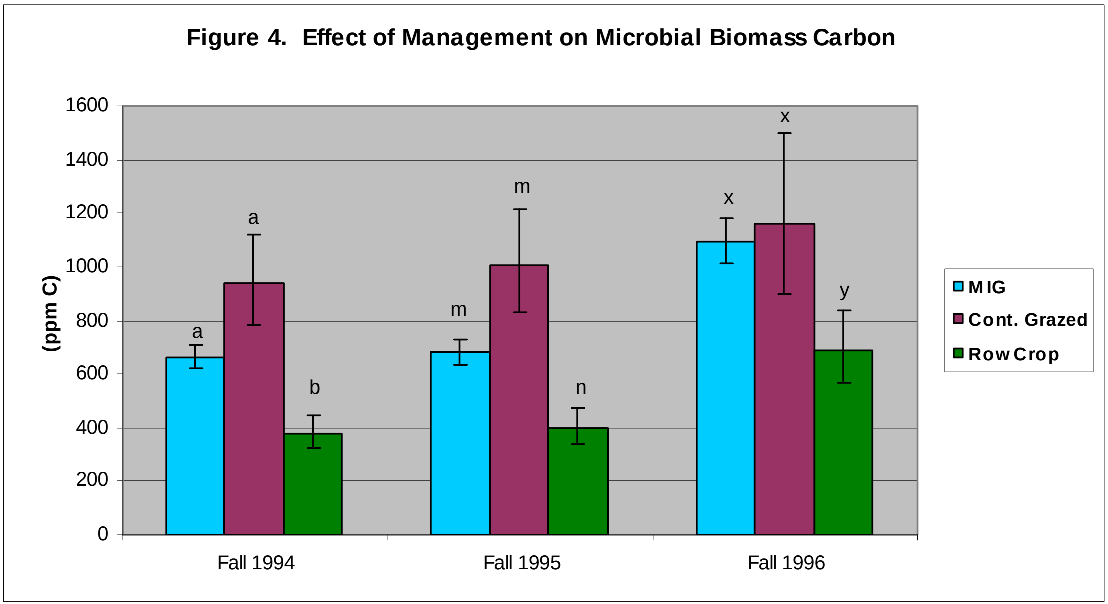
Table 8. Soil Moisture Content by Management at Biological Sampling Events, 1994-2002

	Gravimetric % H_2O at sampling for biological parameters			
	Fall 1994	Fall 1995	Fall 1996	Fall 2002
MIG	27.8 (5.3)*	27.6 (5.5)	24.2 (5.9)	31.1 (6.1)
Continuous Grazing	33.3 (7.3)	33.6 (9.1)	27.4 (1.7)	30.9 (1.1)
Row Crop	20.0 (6.6)	29.6 (5.9)	26.1 (6.1)	31.8 (2.8)

*-Values represent mean (standard deviation).

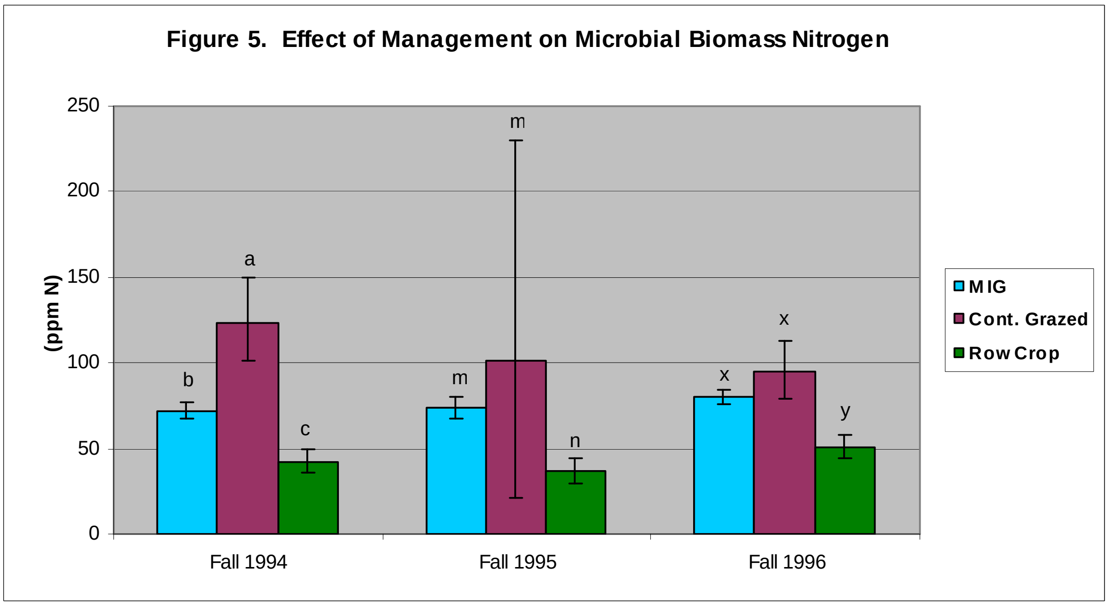


-Columns represent means (error bars represent mean less one standard deviation, mean plus one standard deviation) after back-transformations of log-transformed statistics.
-Columns marked with different letters within groups are significantly different at $p< 0.05$, except in 1995, when differences were significant at $p< 0.10$.



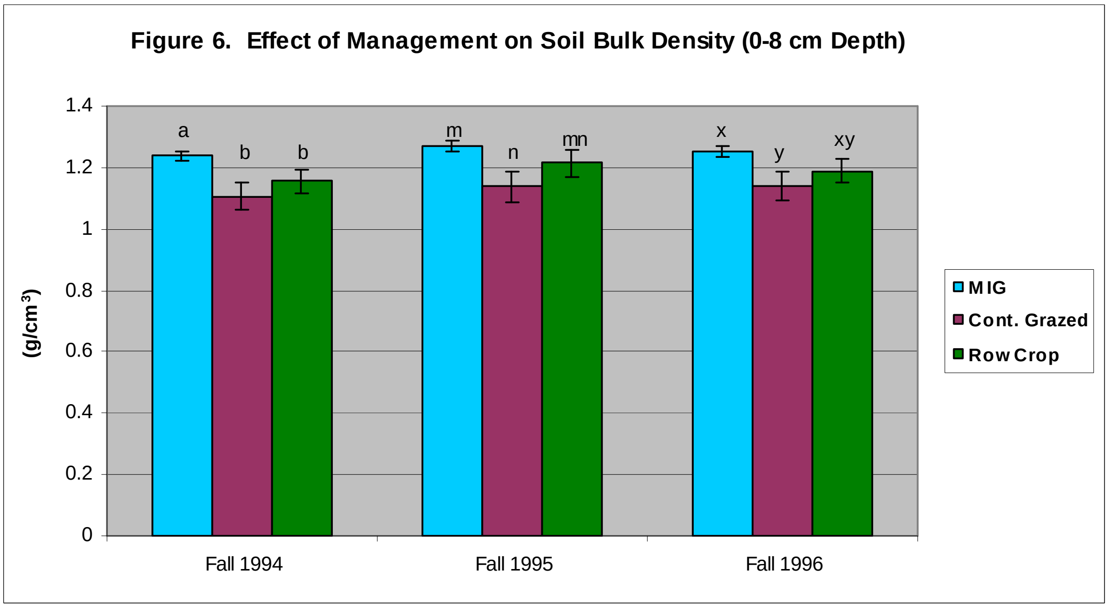
-Columns represent means (error bars represent mean less one standard deviation, mean plus one standard deviation) after back-transformations of log-transformed statistics.
-Columns marked with different letters within groups are significantly different at $p< 0.05$, except in 1996, when differences were significant at $p< 0.10$.

Microbial biomass nitrogen was not as affected by sampling conditions as respiration rate and MBC in 1996. Under continuous grazing, MBN was either significantly greater (in 1994) or equal to MIG (1995 and 1996). Levels under CG were nearly double those under RC at each sampling time from 1994 through 1996.

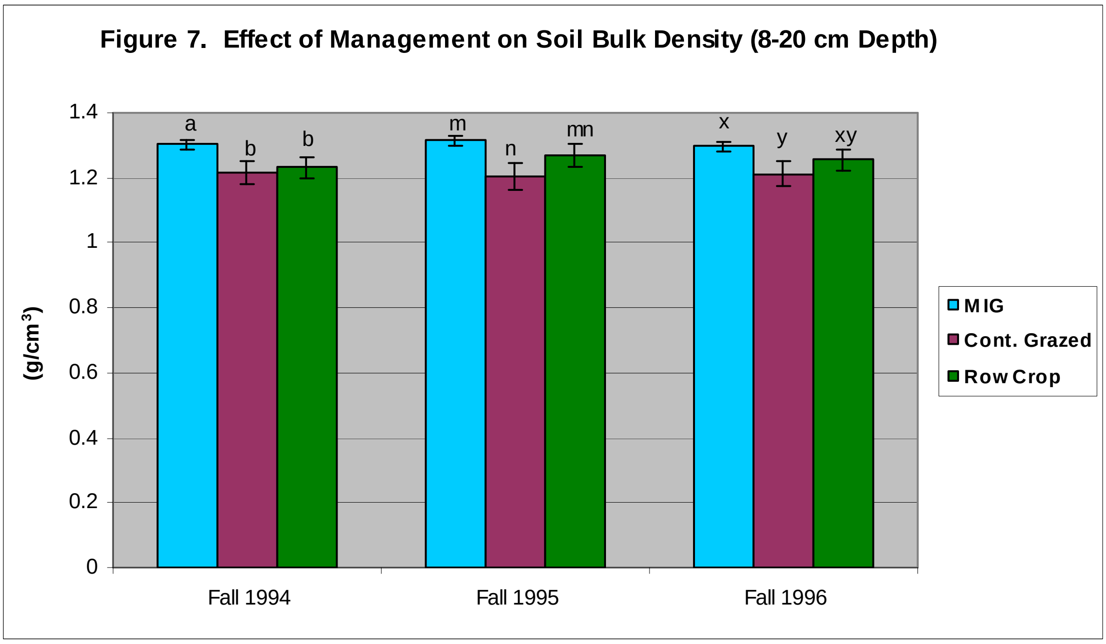


-Columns represent means (error bars represent mean less one standard deviation, mean plus one standard deviation) after back-transformations of log-transformed statistics.
-Columns marked with different letters within groups are significantly different at p< 0.05.

Soil bulk density was highest under MIG and lowest under CG, with RC consistently falling in-between. This pattern was significant ($p < 0.05$), and repeated in each year over the 0-8 and 8-20 cm depths (Figures 6 and 7).



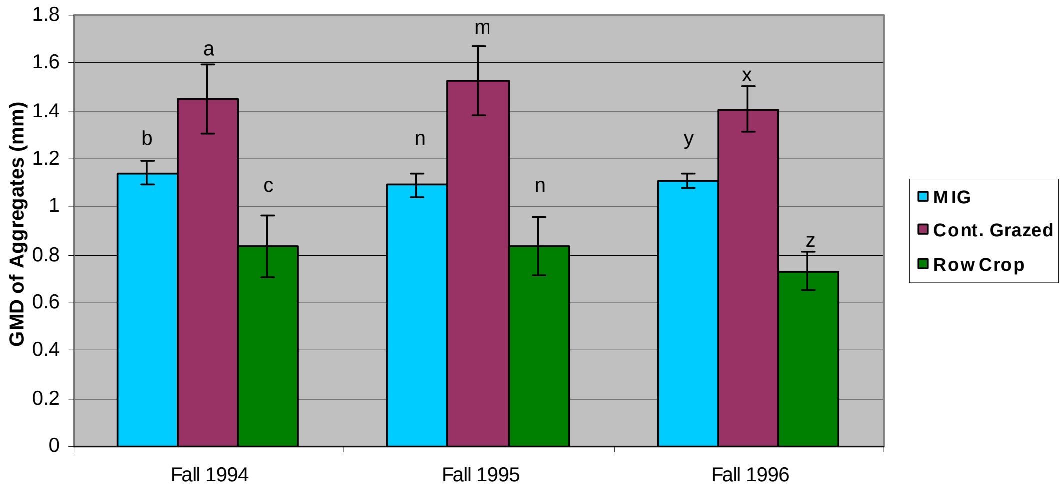
-Columns represent means (error bars represent mean less one standard deviation, mean plus one standard deviation).
-Columns marked with different letters within groups are significantly different at p< 0.05.



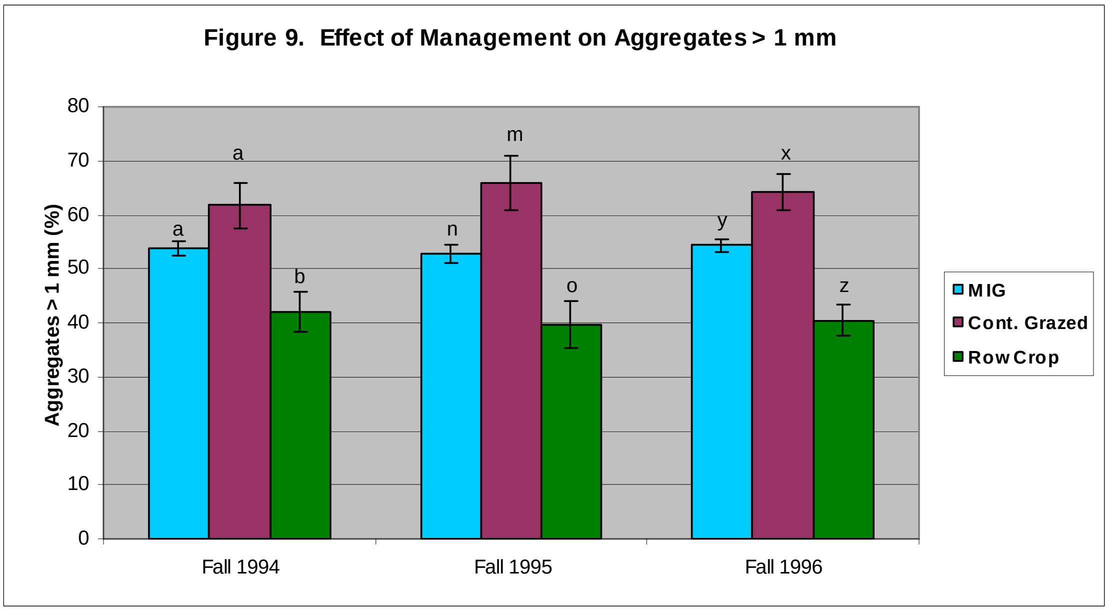
-Columns represent means (error bars represent mean less one standard deviation, mean plus one standard deviation).
-Columns marked with different letters within groups are significantly different at p< 0.05, except in 1996, when differences were significant at p< 0.10.

Two indices of soil structure, geometric mean diameter (GMD) and the percentage of aggregates greater than 1 mm in diameter (AGG), exhibited clear and consistent trends. At each sampling time, GMD and AGG were greatest under CG, followed by MIG, which was in turn greater than RC (Figures 8 and 9).

Figure 8. Effect of Management on Geometric Mean Diameter



-Columns represent means (error bars represent mean less one standard deviation, mean plus one standard deviation).
-Columns marked with different letters within groups are significantly different at $p< 0.05$.



-Columns represent means (error bars represent mean less one standard deviation, mean plus one standard deviation).
-Columns marked with different letters within groups are significantly different at p< 0.05.

Soil pH showed significant management differences only in 1996 (p< 0.10). Soils under MIG had the highest pH. Continuously grazed plots had the lowest pH, and row crop plots yielded intermediate readings (Table 9).

Table 9. Effect of Management on Soil pH

	pH (1:1 H2O Slurry)		
Management	Fall 1994	Fall 1995	Fall 1996
MIG	6.51 (0.07)*	6.52 (0.08)	6.46a (0.09)**
CG	6.33 (0.21)	6.15 (0.23)	5.89ab (0.24)
RC	6.35 (0.18)	6.45 (0.20)	6.26b (021)
MG-RC p-value	ns	ns	0.377
MG-CG p-value	ns	ns	0.030
CG-RC p-value	ns	ns	0.233

*-Values represent mean (standard deviation).
**-Numbers within a column followed by different letters are significantly different at p< 0.10.

Soil phosphorus concentrations were not statistically different (Table 10). The only differences observed in soil potassium measurements were in fall 1994, when CG was higher than MIG (Table 10).

Table 10. Effect of Management on Chemical Indicators of Soil Quality

	Bray Phosphorus			Ammonium Acetate Ext. Potassium		
	Fall 1994	Fall 1995	Fall 1996	Fall 1994	Fall 1995	Fall 1996
Management	**(ppm P)**	**(ppm P)**	**(ppm P)**	**(ppm K)**	**(ppm K)**	**(ppm K)**
MIG	21.12 (18.00, 24.77)*	19.41 (16.87, 22.35)	20.24 (17.05, 24.03)	126b (117, 136)**	129 (121, 137)	161 (148, 174)
CG	14.19 (8.91, 22.57)	11.58 (7.69, 17.44)	10.49 (6.56, 16.80)	232a (190, 288)	151 (127, 181)	188 (152, 233)
RC	36.65 (24.56, 54.70)	24.91 (17.05, 35.45)	29.42 (19.59, 44.18)	162ab (134, 195)	162 (139, 189)	184 (153, 221)
MG-RC p-value	ns	ns	ns	0.211	ns	ns
MG-CG p-value	ns	ns	ns	0.010	ns	ns
CG-RC p-value	ns	ns	ns	0.198	ns	ns

*-Values represent mean (mean less one standard deviation, mean plus one standard deviation) after back-transformations of log-transformed statistics.

**-Numbers within a column followed by different letters are significantly different at $p < 0.05$.

Effects of Management Intensive Grazing Between 1994 and 2002

Between plot establishment and the final sampling in 2002, access to a number of measurement sites was lost. The reduced number of plots meant that comparison among the three management systems was no longer possible. Instead, two-sample t-tests were conducted on data from the remaining MIG plots to quantify changes between 1994 and 2002.

Direct measurement of organic matter by Loss-on-Ignition did not change significantly from 1994 to 2002. On the other hand, TOC and Total N did increase and the C/N ratio narrowed ($p < 0.05$) in the eight years following conversion to MIG management (Table 11).

Table 11. Organic Matter Measures in 1994 and 2002

	1994 mean	**2002 mean**	**p-value**	**df**
LOI (% by weight)	5.111	5.333	0.631	41.06
TOC (% C)*	2.194	2.783	0.017	41.39
TON (% N)*	0.194	0.270	<0.001	40.33
TOC/N	11.81	10.66	<0.001	38.19

*-Values represent means after back-transformations of log-transformed statistics.
All MIG plots sampled in 1994 and 2002 (n=22).

Particulate Organic Matter (POM) was measured in MIG plots in 1996 and 2002. During that period, measures of POM carbon and nitrogen content decreased by half (Table 12). Because other measures of labile organic matter pools were also quite different in 1996 compared to other years, it appears likely that this difference may be an artifact of seasonal variability rather than a true decline in amounts of POM over time.

Table 12. Particulate Organic Matter in 1996 and 2002

	1996 mean	2002 mean	p-value	df
POM C (mg/g soil)*	7.86	3.84	<0.001	38.76
POM C/TOC (%)	28.9	14.9	<0.001	40.93
POM N (µg/g soil)*	457	198	<0.001	34.24
POM N/Total N (%)*	17.4	7.56	<0.001	30.66
POM C/N	17.4	20.3	0.062	28.58

*-Values represent means after back-transformations of log-transformed statistics.
All MIG plots sampled in 1996 and 2002 (n=22).

Microbial biomass respiration was lower in 2002 ($p < 0.10$), but that may have been due to unseasonably cold conditions prior to sampling (Table 7). Two other biological indicators of soil quality, MBC and MBN, both increased by nearly 40% over the period 1994-2002 (Table 13). Factoring in the increase in bulk density (see below), biomass C and N increased by more than 55% on a volumetric basis.

Table 13. Biological Indicators of Soil Quality in 1994 and 2002

	1994 mean	2002 mean	p-value	df
Microbial Resp. (ppm C/day)*	21.50	17.91	0.056	32.86
Microbial Biomass C (ppm C)*	652.6	903.6	0.010	41.99
Microbial Biomass N (ppm N)*	73.94	101.9	0.001	37.41
MBC/N	9.014	9.077	0.912	41.97

*-Values represent means after back-transformations of log-transformed statistics.
All MIG plots sampled in 1994 and 2002 (n=22).

Among the 22 MIG plots that remained in 2002, bulk density at both depths (0-8 and 8-20 cm) had increased significantly since 1994 (Table 14), as did Cone Index in the top eight centimeters ($p < 0.10$) (Table 15). Geometric mean diameter and Aggregates > 1 mm did not change between 1994 and 2002.

Table 14. Physical Indicators of Soil Quality in 1994 and 2002

	1994 mean	2002 mean	p-value	df
BD 0-8 cm (g/cm^3)	1.236	1.385	< 0.001	42.00
BD 8-20 cm (g/cm^3)	1.307	1.545	< 0.001	41.11
GMD (mm)	1.115	1.060	0.446	41.70
AGG > 1mm	52.56	51.37	0.562	41.94

All MIG plots sampled in 1994 and 2002 (n=22).

Table 15. Cone Index Measurements MIG in 1994 and 2002

	1994 mean	2002 mean	p-value	df
CI @ 8 cm Depth (Mpa)	1.213	1.403	0.081	29.65
CI over 0-8 cm Depth (Mpa)	1.035	1.321	0.055	26.64
CI @ 23 cm Depth (Mpa)	1.429	1.339	0.365	36.39
CI over 8-23 cm Depth (Mpa)	1.339	1.410	0.425	29.52
CI over 0-23 cm Depth (Mpa)	1.253	1.399	0.141	26.68
CI 8 cm /23 cm Ratio	0.871	1.067	0.015	36.65

All MIG plots sampled in 1994 and 2002 (n=22).

Soil pH did not change under MIG between 1994 and 2002. Bray-extractable phosphorus did increase under MIG, from nearly 25 ppm to 37 under MIG (Table 16).

Table 16. Chemical Indicators of Soil Quality in 1994 and 2002

	1994 mean	2002 mean	p-value	df
pH	6.727	6.777	0.622	39.71
Bray P (ppm P)*	24.48	36.96	0.043	41.92

*-Values represent means after back-transformations of log-transformed statistics.
All MIG plots sampled in 1994 and 2002 (n=22).

DISCUSSION

Many researchers (Houlbrooke et al., 2009, Bowman et al. 1998) have documented the importance of soil organic matter in maintaining healthy, productive, sustainable ecosystems. Organic matter is related to nearly all biological, chemical, and physical indicators of soil quality. The measures of organic matter tracked in this study (total soil C and N, particulate organic matter C and N, microbial biomass C and N, and microbial respiration rate) generally exhibited similar trends and relationships. For many of these parameters, levels were higher for management intensive grazing and continuous grazing than for row crop. Most biological indicators of soil quality increased between 1994 and 2002. During the period 1994-1996, when management comparisons were possible, microbial biomass levels under MIG were nearly double those under RC. Using these measures as indicators of soil quality, MIG and CG would be considered to out-perform RC management, the basic premise being that the more microbial activity, the healthier the soil (Troeh and Thompson, 1993).

A plot's position within the landscape appears to have impacted its carbon and nitrogen status. When results were significant (Table 6), TOC and Total N tended to be higher at low points in the landscape. Microbial biomass carbon and nitrogen generally followed the same pattern, indicating that organic matter cycling and biological activity are greatest in those areas (Appendix C). Increases in Total C and N under MIG, combined with narrowing TOC/N ratio, indicate that more organic matter is being cycled through the soil, and that the C/N composition is approaching the "baseline" soil organic matter ratio of approximately 10:1 ratio (Troeh and Thompson, 1993).

Sharp decreases in POM shown in this study (Table 12) may be artifacts of temperature and moisture conditions, but they also may indicate that mineralization rates are accelerated under MIG. Furthermore, the widening POM C/N ratios may indicate that the process is N-limited, and that the most labile organic matter pools are being utilized at least as quickly as they can be replenished. More measurements are needed to determine what trends, if any, are developing.

Bulk density results show that the greatest compaction occurred under MIG, followed by RC and CG. Combined with aggregate stability and cone index results, it appears that physical condition of the soil is directly related to the timing and extent of the disturbance caused by the managements employed. Arevalo et. al (1998), Drewry (2006) and others have shown most of the physical impacts of grazing to occur in the top 10-15 cm of the soil. Below that depth, physical damage from livestock traffic is unlikely to occur under ordinary circumstances, though compaction from tillage equipment may still occur. Management intensive grazing may mimic a natural system in which herd migration would likely result in similar “periodic” pressure (Fuhlendorf and Engle, 2001). Varied responses to grazing may be expected due to differing grazing histories, as sites may be differentially adapted to withstand grazing pressure (Milchunas and Lauenroth, 1993, Anderson, 2000).

It is likely that elevated bulk densities at high points in the landscape are directly related to erosion of topsoil and deposition to lower positions (Appendix D). Recurring disturbance by MIG practices may hasten those processes. Much like conservation tillage in row crop management, care must be taken to minimize physical disturbance of the soil under MIG, especially in highly erodible areas, or in times of increased vulnerability, such as when soil is wet.

Increases in Bray P under MIG between 1994 and 2002 may be directly attributable to animal waste inputs (Table 16). As noted by Gerrish et al (1995), distance that cattle travel to water can lead to nutrient gradients across pastures. Further systematic monitoring may help to identify such patterns, and lead to a better understanding of pasture utilization under MIG.

CONCLUSION

Several indicators of soil quality were measured, in hopes of quantifying the effects of management intensive grazing (MIG), continuous grazing (CG), and row crop (RC) management systems. For most organic matter measures, MIG and CG management were superior to RC. For physical measures of soil quality, CG yielded superior results to the other management systems. The consistent, low-intensity disturbance from CG closely resembles native rangeland, and should provide the best situation for the maintenance of soil structure among the three systems studied. Under RC, physical indicators were intermediate, while MIG plots showed the poorest results. This may be due to the rapid and concentrated disturbance and shorter recovery time between grazing events relative to tillage and cultivation under RC, as well as the impact of animal traffic on wet ground.

Inconclusive results among chemical indicators suggest that further monitoring and careful management would be required to accurately categorize long-term soil quality impacts and ensure the sustainability of these systems over time.

The primary conclusions to be drawn from this work are that MIG and CG often out-perform row cropping in terms of most physical and biological measures of soil quality. Measurements of geometric mean diameter of soil aggregates, aggregates greater than 1 mm in diameter, microbial respiration rate and microbial biomass C and N levels would all be classified as “better” or “improved” under MIG and CG as opposed to RC in this study. On the other hand, bulk density measurements were consistently lower under RC than MIG. Cone index, while still below the 2.0 Mpa threshold for root growth limitation, trended upward under MIG, especially near the soil surface. Chemical indicators of soil quality, including pH, potassium, and phosphorus measurements showed inconclusive results, which may be due to temporal and/or spatial variability, as much as to treatment effects.

This research has shown that management intensive grazing can help to build up levels of organic matter and biological activity in the soil. And though aggregation can be enhanced, soil compaction from MIG management should be controlled by minimizing animal traffic under wet conditions or in unstable landscapes. Nutrient levels must also be carefully managed, as inputs from animal waste can lead to excessive N, P, and K in the soil. A comprehensive soil quality monitoring plan may help to identify problems as they develop, or to minimize those problems from the outset.

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Appendix A. Summary of Plot Background Information.

Plot	Soil Series	Profile	Position	Drainage	Texture	Previous MGMT	Establishment Year*	MGMT	Sampled in 2002
F1	Mt. Carroll	Ap, E, BE	Top	Well	SiL	RC	1991	MG	X
F2	Mt. Carroll	Ap, E, BE	Mid	Well	SiL	RC	1991	MG	
F3	Spillville	A1	Bottom	Well	L	CG	1990	MG	X
F4	Mt. Carroll	Ap, E, BE	Top	Well	SiL	RC	1991	MG	X
F5	Spillville	A1	Bottom	Well	L	RC	1991	MG	X
F6	Racine	A, E	Mid	Well	SiCL	Hay	1994	MG	
F7	Racine	A, E	Mid	Well	SiCL	RC	1994	MG	
F8	Whalan	A1, A2, B1	Mid	Well	SiL	RC	1994	MG	X
F9	Whalan	A1, A2, B1	Mid	Well	SiL	Hay	1994	MG	X
F10	Spillville	A1	Bottom	Well	L	CG	1990	MG	X
FC	Mt. Carroll	Ap, E, BE	Top	Well	SiL	RC	1979	RC	
FP	Spillville	A1	Bottom	Well	CL	CG	1979	CG	
M1	Lester	Ap, Bt1	Top	Well	CL	RC/Hay	1994	MG	
M2	Lester	Ap, Bt1	Top	Well	CL	RC/Hay	1994	MG	X
M3	LeSueur	Ap, A	Mid	Moderate	CL	RC/Hay	1994	MG	X
M4	Cordova	Ap, A	Bottom	Poor	CL	RC/Hay	1994	MG	
M5	Lester	Ap, Bt1	Mid	Well	CL	RC/Hay	1994	MG	
M6	Webster	Ap, A	Bottom	Poor	CL	RC/Hay	1994	MG	
M7	Comfrey	Ap, A	Bottom	Poor	CL	RC/Hay	1993	MG	X
M8	Comfrey	Ap, A	Bottom	Poor	C	RC/Hay	1993	MG	
M9	Lester	Ap, Bt1	Top	Well	CL	RC	1992	MG	X
M10	LeSueur	Ap, A	Mid	Moderate	CL	RC	1992	MG	
M11	Cordova	Ap, A	Bottom	Poor	CL	RC	1992	MG	X
M12	LeSueur	Ap, A	Mid	Poor	CL	RC	1992	MG	
M13	Hamel	Ap, A	Bottom	Poor	CL	RC	1992	MG	
MC1	Lester	Ap, Bt1	Top	Well	CL	RC	1989	RC	
MC2	Webster	Ap, A	Bottom	Poor	C	RC	1989	RC	
MC3	Hamel	Ap, A	Bottom	Poor	CL	RC	1989	RC	X
MC4	Hamel	Ap, A	Bottom	Poor	CL	RC	1989	RC	X
MP	Lester	Ap, Bt1	Top	Well	CL	RC	1989	CG	
R1	Mt. Carroll	Ap, E, BE	Top	Well	SiCL	RC	1993	MG	X
R2	Eitzen	Ap, C	Bottom	Well	SiCL	RC	1993	MG	X
R3	Mt. Carroll	Ap, E, BE	Top	Well	SiCL	RC/Hay	1987	MG	X
R4	Mt. Carroll	Ap, E, BE	Top	Well	SiCL	RC/Hay	1994	MG	X
R5	Mt. Carroll	Ap, E, BE	Top	Well	SiCL	RC/Hay	1993	MG	X
R6	Eitzen	Ap, C	Bottom	Well	SiCL	RC/Hay	1992	MG	X
RC	Mt. Carroll	Ap, E, BE	Top	Well	SiCL	RC	1989	RC	X
RC2	Eitzen	Ap, C	Bottom	Well	SiCL	RC	1989	RC	X
RP	Eitzen	Ap, C	Bottom	Well	SiL	RC	1984	CG	
RP2	Eitzen	Ap, C	Bottom	Well	SiL	CG	1984	CG	X
RP3	Eitzen	Ap, C	Bottom	Well	SiL	CG	1984	CG	X

Appendix A continued. Summary of Plot Background Information.

Plot	Soil Series	Profile	Position	Drainage	Texture	Previous MGMT	Estab. Year	MGMT	Sampled in 2002
T1	Rollingstone	Ap, BE	Top	Well	SiC	RC	1992	MG	**X**
T2	Seaton	Ap, E, BE	Bottom	Well	SiL	RC	1992	MG	
T3	Rollingstone	Ap, BE	Top	Well	SiCL	RC	1992	MG	**X**
T4	Seaton	Ap, E, BE	Bottom	Well	SiL	RC	1992	MG	**X**
T5	Rollingstone	Ap, BE	Top	Well	SiCL	RC	1993	MG	**X**
TC1	Rollingstone	Ap, BE	Top	Well	SiCL	RC/Hay	1984	RC	
TC2	Rollingstone	Ap, BE	Top	Well	SiCL	RC/Hay	1984	RC	
TP	Rollingstone	Ap, BE	Top	Well	SiCL	CG	1984	CG	**X**
J1	Haverhill	A, AB	Mid	Poor	CL	RC/Hay	1993	MG	
J2	Haverhill	A, AB	Mid	Poor	C	RC/Hay	1993	MG	
J3	Frankville	Ap, BE	Top	Well	L	RC/Hay	1994	MG	
J4	Frankville	Ap, BE	Top	Well	SiL	RC/Hay	1994	MG	
JC	Frankville	Ap, BE	Top	Well	SiL	RC	1964	RC	
JP	Frankville	Ap, BE	Top	Well	SiL	CG	1964	CG	
L1	Zwingle/Medary	A, E	Bottom	Poor	SiCL	RC/Hay	1983	MG	
L2	Zwingle/Medary	A, E	Bottom	Poor	SiCL	RC/Hay	1993	MG	
L3	Zwingle/Medary	A, E	Bottom	Poor	SiCL	RC/Hay	1993	MG	
L4	Zwingle/Medary	A, E	Bottom	Poor	SiCL	RC/Hay	1993	MG	
L5	Zwingle/Medary	A, E	Bottom	Poor	SiCL	RC/Hay	1993	MG	

Appendix B. Details and Adjustments to Methods Cited

Total Carbon and Nitrogen

Total carbon (TOC) and nitrogen (TON) were measured by dry combustion. Samples were sieved < 2 mm to remove stones and large pieces of organic matter, air dried, and analyzed for total carbon and nitrogen using a LECO CN-2000.

Organic Matter Content

Organic matter content was determined by the loss on ignition (LOI) method as described by Schulte (1988). Soil was sieved to < 2 mm to remove stones and plant debris, then air-dried at room temperature for 10-14 days. Samples weighing approximately 2 grams each were placed in porcelain crucibles of known weight and oven-dried at 105^o C for 2 hours. Samples were then weighed hot to negate the effects of ambient humidity and placed in a 360^o C muffle furnace. Samples were allowed to combust for two hours. Samples were returned to the 105^o C oven for two hours prior to final weighing, to again counteract the effects of ambient humidity. Organic matter loss on ignition was represented as percent lost by weight:

$$\%LOI = 100 * \left[1 - \frac{net\ wt.\ of\ \ combusted\ soil}{net\ wt.\ of\ \ non-combusted\ soil} \right]$$

Particulate Organic Matter

Particulate organic matter (POM) carbon and nitrogen was determined by passing dispersed soil samples through a 53 µm polyester mesh cloth (Gilson, Columbus, OH) following the Wander and Bollero (1999) method with some modifications. Specifically, 30 ml of 10% sodium metaphosphate was used as the dispersant rather than 20 ml of 5% sodium metaphosphate. The use of additional dispersant of increased strength was found to be necessary for the soils of this study, which were particularly resistant to chemical dispersion due to high levels of clay and organic matter. Samples consisting of POM and sand were ball milled to a powdery texture and analyzed for total carbon and nitrogen by dry combustion using a LECO CN-2000.

Moisture Content

Soil water content was determined for three sets of samples collected from each sampling window. Intact bulk density samples were used to determine moisture content. Subsamples were taken for moisture determination from soils used to measure microbial biomass, and from those used for aggregate stability. Water content was determined gravimetrically using the technique described by Gardner (1986). Soil samples were weighed “field moist”, then dried for 48 hours at 105^o C, and weighed again. Soil moisture content, as a percentage, was calculated as follows:

$$\%H_2O = 100 * \left[\frac{net\ wet\ wt.\ of\ soil - net\ dry\ wt.\ of\ soil}{net\ dry\ wt.\ of\ soil} \right]$$

Microbial Biomass Carbon and Nitrogen

Samples for soil biological measurements were collected in late fall each year (mid-October through early December), after plant growth had largely ceased and microbial activity was expected to be at baseline levels.

Core samples from the 0-8 cm depth were sieved to < 2 mm to remove stones and intact plant material, and kept in a field-moist condition pending processing. Microbial biomass carbon, nitrogen and respiration rate were determined using a modification of the fumigation procedure described by Jenkinson and Powlson (1976), and Vance et al. (1987). Specifically, 25 g of field moist soil were fumigated with chloroform ($CHCl_3$) for 48 hours. Soils were then incubated in 1-quart mason jars, with 20 ml of NaOH serving as the alkali trap. Alkali traps were analyzed for total inorganic carbon using a Tekmar Dohrmann Phoenix 8000 Carbon Analyzer (Teledyne Tekmar, Mason, OH). Microbial biomass carbon production was calculated as the difference between CO_2 evolved from fumigated subsamples and CO_2 evolved from non-fumigated control soil, divided by a fractionation coefficient.

$$MBC = \left[\frac{fumigated - control}{.45} \right]$$

A fractionation coefficient (*k*) of 0.45 (Sparling and Ross, 1993) was used to account for the fraction of biomass carbon that is mineralized to CO_2 during the incubation period. A k-factor of 0.45 has been shown to be appropriate for surface soils and agronomic treatment comparisons (Carter et al., 1999).

Microbial respiration rate was determined as the amount of CO_2 evolved from the non-fumigated (control) replicates. Total CO_2 evolved over the 10-day incubation is considered to reflect baseline respiration rates.

Microbial biomass nitrogen was determined by KCl extraction of fumigated and non-fumigated subsamples. After the 10-day incubation period, mineral nitrogen was extracted from a 3.5-g moist soil subsample using 2M KCl. The difference between paired fumigated and non-fumigated control soils is attributed to microbial activity. Mineral nitrogen was analyzed using colorimetric cadmium reduction on a Lachat Quick Chem AE flow injection system (Lachat Instruments, Milwaukee, WI).

Bulk Density

Bulk density was determined with the procedure described by Allmaras et al. (1988), using a specially designed 20.4-mm inner diameter tube sampler with a 19-mm diameter cutting tip. Each sample was divided into depth increments with each segment placed into separate storage containers (soil moisture tins). For the initial sampling in 1994, samples were divided into 2-cm depth increments. For all subsequent samplings, 5-cm increments were used. Due to the difficulty in obtaining good cores through the full range of depths, results are presented only to a depth of 20 centimeters.

Aggregate Stability

Wet aggregate stability was determined using a nested wet sieving technique adapted from Kemper and Chepil (1965). Samples were passed through an 8-mm sieve to remove large stones and fresh organic matter. The samples were then air-dried at room temperature. Fifty grams of air dried soil was placed on the top-most of a nest of five sieves suspended over a column of room temperature water (18-23^{o} C, 65-73 ^{o} F). Samples were then re-wetted at atmospheric pressure via slaking. The soil was then allowed to soak fully immersed in water for 10 minutes. Samples were then sieved for 10 minutes using a shaker similar in style to that described by Yoder (1936) (30 rpm, 1.5" stroke length) in that same water. The sieve sizes were 4 mm, 2 mm, 1 mm, 0.5 mm, and 0.25 mm. Material from each of the sieves was collected in separate beakers, dried at 105˚C for 48 hours, and weighed to determine the amount of water-stable aggregates remaining in each size class. The < 0.25 mm size class was calculated by difference, as it is assumed to be the difference between the initial sample weight and the final weight of the captured aggregates. Geometric mean diameter (GMD) was calculated to represent aggregate size distribution as follows:

$$GMD = \log^{-1}\left[\frac{\sum_{i=1}^{n} w_i \log \bar{x}_i}{\sum_{i=1}^{n} w_i}\right]$$

Where w_i is the weight of aggregates in a given size class, $\bar{x}_i$ is the average diameter of aggregates in that size class and $\sum_{i=1}^{n} w_i$ is the total sample weight.

The weight of aggregates greater than 1 mm in diameter was also calculated and is presented as a separate measurement. Macroaggregates greater than 1 mm in diameter have been shown to be of particular importance in organic matter dynamics (Aoyama et. al, 1999). Aggregates of such size can envelope and protect organic matter particles, thereby serving to regulate the rate of organic matter breakdown and cycling.

Cone Index

Cone index, a measure of penetration resistance, was determined by measuring the force needed to push a 1.27-cm, 30^{o} cone-tipped probe through the soil. The force applied was divided by the basal area of the cone and is reported in megaPascals (MPa). Cone index was determined using the Bush Recording Soil Penetrometer (Findlay, Irvine Ltd., Midlothian, Scotland). The unit was set up to record penetration resistance at 2.5-cm intervals to a depth of 30 cm. We routinely encountered rocks or other obstructions at depths that likely coincided with the historical plow layer. Due to uncertainties about the quality of data near the bottom of the measurement range, results are only reported to a depth of 23 centimeters.

Chemical Analysis

Core samples were collected in the fall, after the growing season, and were sieved to < 2 mm and air-dried. Standard soil chemical tests for pH, phosphorus, and potassium were performed. Soil pH was measured in a 1:1 water slurry. Phosphorus was tested using the Bray-1 method (Kuo, 1996). Potassium was measured as ammonium acetate extractable.

Statistical Analysis

Data were tested for normality using the Shapiro-Wilk test procedure in PROC UNIVARIATE (SAS Institute, 2002). Non-normal distributions were log-transformed to approximate normality. Variables for which normality was improved by log-transformation included TOC, total soil N, microbial respiration rate, MBC, MBN, POM C, POM N, POM NN, Bray P, and ammonium acetate extractable K. Data that required transformation were converted to log-normal for statistical analysis, then back-transformed for reporting. Because the normality of bulk density from the 0-8 and 8-20 cm depths, GMD, Aggregates > 1mm, and soil pH data did not improve with transformation, the untransformed data were used for statistical analysis.

Analysis of variance was performed using PROC Mixed (SAS Institute, 2002) to evaluate management and topographical differences within sampling dates from 1994 through 1996. Means were compared using the PDIFF option of the LSMEANS statement. Two sample t-tests were conducted in the R (version 2.90) Statistical Package (Freeware, available at www.r-proj.org) to determine changes between plot establishment in 1994 and the final sampling in 2002 for most indices, and between 1996 and 2002 in the case of POM measurements.

Representative graphs and tables were produced with Microsoft Excel, 2003.

Appendix C. Effect of Management on Soil Quality Indicators

	Total Organic Carbon (% C)			p-values		
	MIG	CG	RC	MIG vs. RC	MIG vs. CG	CG vs. RC
Fall 1994	2.40 (2.26, 2.55)*	2.52 (2.11, 3.01)	2.58 (2.21, 3.00)	ns	ns	ns
Fall 1995	3.00 (2.83, 3.17)	3.42 (2.90, 4.04)	2.55 (2.21, 2.94)	ns	ns	ns
Fall 1996	2.68 (2.53, 2.84)	2.76 (2.34, 3.25)	2.79 (2.42, 3.21)	ns	ns	ns

	Total Organic Nitrogen (% N)			p-values		
	MIG	CG	RC	MIG vs. RC	MIG vs. CG	CG vs. RC
Fall 1994	0.21 (0.20, 0.22)	0.25 (0.22, 0.29)	0.23 (0.20, 0.26)	ns	ns	ns
Fall 1995	0.27a (0.25, 0.28)**	0.34a (0.29, 0.38)	0.19b (0.16, 0.22)	0.038	0.125	0.007
Fall 1996	0.28 (0.25, 0.32)	0.45 (0.34, 0.56)	0.27 (0.19, 0.35)	ns	ns	ns

	mg POM C/g soil			p-values		
	MIG	CG	RC	MIG vs. RC	MIG vs. CG	CG vs. RC
Fall 1994	---	---	---	---	---	---
Fall 1995	---	---	---	---	---	---
Fall 1996	7.09a (6.66, 7.55)**	8.00a (6.67, 9.59)	4.07b (3.48, 4.76)	0.002	0.531	0.006

	POM C/TOC (%)			p-values		
	MIG	CG	RC	MIG vs. RC	MIG vs. CG	CG vs. RC
Fall 1994	---	---	---	---	---	---
Fall 1995	---	---	---	---	---	---
Fall 1996	25.13a (1.45)# **	30.58a (4.22)	18.11b (3.64)	0.075	0.221	0.025

	μg POM N/g Soil			p-values		
	MIG	CG	RC	MIG vs. RC	MIG vs. CG	CG vs. RC
Fall 1994	---	---	---	---	---	---
Fall 1995	---	---	---	---	---	---
Fall 1996	407a (381, 434)**	467a (386, 587)	245b (207, 288)	0.006	0.488	0.011

	POM N/Total N (%)			p-values		
	MIG	CG	RC	MIG vs. RC	MIG vs. CG	CG vs. RC
Fall 1994	---	---	---	---	---	---
Fall 1995	---	---	---	---	---	---
Fall 1996	14.93a (14.12, 15.76)**	17.65a (15.11, 20.65)	10.67b (9.33, 12.21)	0.023	0.310	0.015

*-Values represent mean (mean less one standard deviation, mean plus one standard deviation) after back-transformations of log-transformed statistics.

#-Values represent mean (standard deviation) for normally distributed statistics.

**-Numbers within a row followed by different letters are significantly different at $p < 0.05$.

Appendix C continued. Effect of Management on Soil Quality Indicators

	Microbial Biomass Respiration Rate (ppm C/day)			p-values		
	MIG	CG	RC	MIG vs. RC	MIG vs. CG	CG vs. RC
Fall 1994	20.0a (18.65, 21.42)* **	19.71a (16.12, 24.10)	12.37b (10.40, 14.72)	0.013	0.947	0.076
Fall 1995	20.56m (19.28, 21.97)$^{\Psi}$	22.50m (18.57, 27.27)	13.56n (11.49, 16.00)	0.022	0.654	0.044
Fall 1996	38.55x (36.74, 40.45) **	37.09x (32.24, 42.67)	23.71y (21.02, 26.75)	0.001	0.793	0.016

	Microbial Biomass Carbon (ppm C)			p-values		
	MIG	CG	RC	MIG vs. RC	MIG vs. CG	CG vs. RC
Fall 1994	664a (624, 706)**	937a (782, 1123)	381b (326, 445)	0.002	0.074	<0.001
Fall 1995	681m (637, 727)**	1005m (831, 1216)	398n (338, 469)	0.004	0.056	<0.001
Fall 1996	1094x (1010, 1185)$^{\Psi}$	1161x (900, 1498)	690y (570, 836)	0.031	0.823	0.096

	Microbial Biomass Nitrogen (ppm N)			p-values		
	MIG	CG	RC	MIG vs. RC	MIG vs. CG	CG vs. RC
Fall 1994	72.03b (67.40, 77.00)**	123a (102, 150)	42.09c (35.65, 49.69)	0.004	0.011	<0.001
Fall 1995	73.51m (67.80, 79.70)**	101m (21.20, 230)	36.60n (29.88, 44.82)	0.002	0.197	0.002
Fall 1996	80.22x (76.09, 84.58)**	94.41x (79.09, 113)	50.75y (44.44, 57.95)	0.002	0.378	0.006

	Bulk Density (0-8 cm Depth) (g/cm^3)			p-values		
	MIG	CG	RC	MIG vs. RC	MIG vs. CG	CG vs. RC
Fall 1994	1.24a (0.02)# **	1.11b (0.05)	1.16b (0.04)	0.049	0.007	0.387
Fall 1995	1.27m (0.02)**	1.14n (0.05)	1.21mn (0.04)	0.253	0.02	0.251
Fall 1996	1.25x (0.02)**	1.14y (0.05)	1.19xy (0.04)	0.127	0.019	0.38

	Bulk Density (8-20 cm Depth) (g/cm^3)			p-values		
	MIG	CG	RC	MIG vs. RC	MIG vs. CG	CG vs. RC
Fall 1994	1.30a (0.01)**	1.22b (0.04)	1.23b (0.03)	0.045	0.034	0.753
Fall 1995	1.32m (0.02)**	1.20n (0.04)	1.27mn (0.04)	0.265	0.018	0.23
Fall 1996	1.30x (0.01)$^{\Psi}$	1.21y (0.04)	1.26xy (0.03)	0.217	0.033	0.367

	Geometric Mean Diameter of Aggregates (mm)			p-values		
	MIG	CG	RC	MIG vs. RC	MIG vs. CG	CG vs. RC
Fall 1994	1.14b (0.05)**	1.45a (0.15)	0.84c (0.13)	0.027	0.049	0.002
Fall 1995	1.09n (0.05)**	1.53m (0.14)	0.83n (0.12)	0.056	0.006	0.001
Fall 1996	1.11y (0.03)**	1.41x (0.09)	0.73z (0.08)	<0.001	0.004	<0.001

*-Values represent mean (mean less one standard deviation, mean plus one standard deviation) after back-transformations of log-transformed statistics.

#-Values represent mean (standard deviation) for normally distributed statistics.

**-Numbers within a row followed by different letters are significantly different at $p< 0.05$.

-Ψ Numbers within a row followed by different letters are significantly different at $p< 0.10$.

Appendix C continued. Effect of Management on Soil Quality Indicators

	Aggregates > 1 mm in Diameter (%)			p-values		
	MIG	CG	RC	MIG vs. RC	MIG vs. CG	CG vs. RC
Fall 1994	53.79a (1.48)# **	61.69a (4.32)	42.00b (3.72)	0.005	0.087	<0.001
Fall 1995	52.83n (1.74)**	65.95m (5.08)	39.63o (4.38)	0.007	0.018	<0.001
Fall 1996	54.34y (1.15)**	64.22x (3.33)	49.49z (2.87)	<0.001	0.007	<0.001

	Soil pH (1:1 H_2O Slurry)			p-values		
	MIG	CG	RC	MIG vs. RC	MIG vs. CG	CG vs. RC
Fall 1994	6.51 (0.07)	6.33 (0.21)	6.35 (0.18)	ns	ns	ns
Fall 1995	6.52 (0.08)	6.15 (0.23)	6.45 (0.20)	ns	ns	ns
Fall 1996	6.46a (0.09)$^{\Psi}$	5.89ab (0.24)	6.26b (021)	0.377	0.030	0.233

	Bray Phosphorus (ppm P)			p-values		
	MIG	CG	RC	MIG vs. RC	MIG vs. CG	CG vs. RC
Fall 1994	21.12 (18.00, 24.77)*	14.19 (8.91, 22.57)	36.65 (24.56, 54.70)	ns	ns	ns
Fall 1995	19.41 (16.87, 22.35)	11.58 (7.69, 17.44)	24.91 (17.05, 35.45)	ns	ns	ns
Fall 1996	20.24 (17.05, 24.03)	10.49 (6.56, 16.80)	29.42 (19.59, 44.18)	ns	ns	ns

	Ammonium Acetate Extractable Potassium (ppm K)			p-values		
	MIG	CG	RC	MIG vs. RC	MIG vs. CG	CG vs. RC
Fall 1994	126b (117, 136)**	232a (190, 288)	162ab (134, 195)	0.211	0.010	0.198
Fall 1995	129 (121, 137)	151 (127, 181)	162 (139, 189)	ns	ns	ns
Fall 1996	161 (148, 174)	188 (152, 233)	184 (153, 221)	ns	ns	ns

*-Values represent mean (mean less one standard deviation, mean plus one standard deviation) after back-transformations of log-transformed statistics.

#-Values represent mean (standard deviation) for normally distributed statistics.

**-Numbers within a row followed by different letters are significantly different at $p < 0.05$.

-Ψ Numbers within a row followed by different letters are significantly different at $p < 0.10$.

Appendix D. Effect of Landscape Position on Soil Quality Indicators

Total Organic Carbon (% C)

	Top	Middle	Bottom	p-values Top vs. Mid	Top vs. Bot	Mid vs. Bot
Fall 1994	1.98a (1.81, 2.17)* **	2.61ab (2.25, 3.03)	3.02b (2.72, 3.36)	0.077	0.001	0.342
Fall 1995	2.80 (2.57, 3.05)	2.86 (2.49, 3.29)	3.26 (2.95, 3.60)	ns	ns	ns
Fall 1996	2.10m (1.93, 2.28)**	3.14n (2.70, 3.65)	3.13n (2.84, 3.45)	0.012	0.001	0.973

Total Nitrogen (% N)

	Top	Middle	Bottom	p-values Top vs. Mid	Top vs. Bot	Mid vs. Bot
Fall 1994	0.183a (0.167, 0.200)**	0.236ab (0.208, 0.265)	0.273b (0.252, 0.294)	0.068	<0.001	0.210
Fall 1995	0.245 (0.224, 0.266)	0.250 (0.216, 0.285)	0.291 (0.266, 0.316)	ns	ns	ns
Fall 1996	0.245 (0.199, 0.293)	0.419 (0.325, 0.520)	0.334 (0.277, 0.394)	ns	ns	ns

mg POM C/g soil

	Top	Middle	Bottom	p-values Top vs. Mid	Top vs. Bot	Mid vs. Bot
Fall 1994	---	---	---	---	---	---
Fall 1995	---	---	---	---	---	---
Fall 1996	6.54 (5.96, 7.18)	5.29 (4.53, 6.17)	6.68 (5.99, 7.44)	ns	ns	ns

POM C/TOC (%)

	Top	Middle	Bottom	p-values Top vs. Mid	Top vs. Bot	Mid vs. Bot
Fall 1994	---	---	---	---	---	---
Fall 1995	---	---	---	---	---	---
Fall 1996	30.05a (2.16)# **	20.93b (3.56)	22.85b (2.52)	0.016	0.016	0.595

μg POM N/g Soil

	Top	Middle	Bottom	p-values Top vs. Mid	Top vs. Bot	Mid vs. Bot
Fall 1994	---	---	---	---	---	---
Fall 1995	---	---	---	---	---	---
Fall 1996	383 (346, 421)	301 (256, 354)	405 (361, 453)	ns	ns	ns

POM N/Total N (%)

	Top	Middle	Bottom	p-values Top vs. Mid	Top vs. Bot	Mid vs. Bot
Fall 1994	---	---	---	---	---	---
Fall 1995	---	---	---	---	---	---
Fall 1996	17.33a (16.00, 18.77)**	11.72b (10.27, 13.37)	13.85b (12.62, 15.21)	0.006	0.042	0.215

*-Values represent mean (mean less one standard deviation, mean plus one standard deviation) after back-transformations of log-transformed statistics.

#-Values represent mean (standard deviation) for normally distributed statistics.

**-Numbers within a row followed by different letters are significantly different at $p < 0.05$.

Appendix D. Effect of Landscape Position on Soil Quality Indicators

Microbial Biomass Respiration Rate (ppm C/day)				p-values		
	Top	Middle	Bottom	Top vs. Mid	Top vs. Bot	Mid vs. Bot
Fall 1994	19.26 (17.37, 21.342)*	15.18 (12.81, 17.99)	16.97 (14.78, 18.80)	ns	ns	ns
Fall 1995	21.62 (19.59, 23.85)	17.56 (14.93, 20.65)	16.54 (14.74, 18.55)	ns	ns	ns
Fall 1996	37.44a (34.85, 40.22)$^{\Psi}$	29.56b (26.26, 33.27)	30.64b (28.18, 33.32)	0.057	0.042	0.763

Microbial Biomass Carbon (ppm C)				p-values		
	Top	Middle	Bottom	Top vs. Mid	Top vs. Bot	Mid vs. Bot
Fall 1994	649 (592, 712)	520 (446, 606)	701(630, 781)	ns	ns	ns
Fall 1995	688a (624, 756)**	495b (422, 581)	800a (714, 896)	0.052	0.250	0.005
Fall 1996	846 (754, 952)	973 (802, 1180)	1065 (914, 1242)	ns	ns	ns

Microbial Biomass Nitrogen (ppm N)				p-values		
	Top	Middle	Bottom	Top vs. Mid	Top vs. Bot	Mid vs. Bot
Fall 1994	68.83a (62.37, 75.95)$^{\Psi}$	62.40a (53.03, 73.41)	87.07b (77.60, 97.70)	0.557	0.080	0.049
Fall 1995	68.18 (60.46, 76.88)	57.78 (47.38, 70.46)	69.22 (60.14, 79.68)	ns	ns	ns
Fall 1996	70.82 (65.29, 76.81)	66.99 (58.62, 76.57)	81.00 (73.21, 89.63)	ns	ns	ns

Bulk Density (0-8 cm Depth) (g/cm^3)				p-values		
	Top	Middle	Bottom	Top vs. Mid	Top vs. Bot	Mid vs. Bot
Fall 1994	1.20a (0.02)$^{\#}$ **	1.19ab (0.04)	1.12b (0.03)	0.781	0.014	0.084
Fall 1995	1.24m (0.03)**	1.24mn (0.04)	1.15n (0.03)	0.997	0.019	0.056
Fall 1996	1.26x (0.02)**	1.16y (0.04)	1.17y (0.03)	0.022	0.004	0.855

Bulk Density (8-20 cm Depth) (g/cm^3)				p-values		
	Top	Middle	Bottom	Top vs. Mid	Top vs. Bot	Mid vs. Bot
Fall 1994	1.29a (0.02)**	1.26a (0.03)	1.20b (0.02)	0.383	<0.001	0.046
Fall 1995	1.31m (0.02)**	1.27mn (0.04)	1.21n (0.03)	0.336	0.002	0.111
Fall 1996	1.32x (0.02)**	1.22y (0.04)	1.22y (0.02)	0.006	<0.001	0.874

Geometric Mean Diameter of Aggregates (mm)				p-values		
	Top	Middle	Bottom	Top vs. Mid	Top vs. Bot	Mid vs. Bot
Fall 1994	1.12 (0.08)	1.16 (0.12)	1.16 (0.09)	ns	ns	ns
Fall 1995	1.14 (0.07)	1.17 (0.12)	1.14 (0.09)	ns	ns	ns
Fall 1996	1.16 (0.05)	1.04 (0.08)	1.05 (0.06)	ns	ns	ns

*-Values represent mean (mean less one standard deviation, mean plus one standard deviation) after back-transformations of log-transformed statistics.

#-Values represent mean (standard deviation) for normally distributed statistics.

**-Numbers within a row followed by different letters are significantly different at p< 0.05.

-Ψ Numbers within a row followed by different letters are significantly different at p< 0.10.

Appendix D continued. Effect of Landscape Position on Soil Quality Indicators

	Aggregates > 1 mm in Diameter (%)			p-values		
	Top	Middle	Bottom	Top vs. Mid	Top vs. Bot	Mid vs. Bot
Fall 1994	51.23 (2.21)#	53.23 (3.64)	53.02 (2.58)	ns	ns	ns
Fall 1995	52.12 (2.60)	53.65 (4.28)	52.65 (3.04)	ns	ns	ns
Fall 1996	55.58 (1.70)	52.10 (2.81)	51.36 (1.99)	ns	ns	ns

	Soil pH (1:1 H_2O Slurry)			p-values		
	Top	Middle	Bottom	Top vs. Mid	Top vs. Bot	Mid vs. Bot
Fall 1994	6.60a (0.11)$^{\Psi}$	6.21b (0.17)	6.38ab (0.12)	0.034	0.126	0.336
Fall 1995	6.60m (0.12)$^{\Psi}$	6.18n (0.19)	6.35mn (0.14)	0.042	0.122	0.392
Fall 1996	6.46x (0.12)$^{\Psi}$	5.98y (0.22)	6.17y (0.14)	0.043	0.084	0.412

	Bray Phosphorus (ppm P)			p-values		
	Top	Middle	Bottom	Top vs. Mid	Top vs. Bot	Mid vs. Bot
Fall 1994	18.53 (14.61, 23.50)*	18.93 (12.79, 28.02)	31.29 (23.70, 41.31)	ns	ns	ns
Fall 1995	16.78 (13.61, 20.68)	15.74 (11.14, 22.23)	21.21 (16.60, 27.09)	ns	ns	ns
Fall 1996	15.44 (12.17, 19.60)	15.14 (9.81, 23.34)	26.73 (20.22, 35.33)	ns	ns	ns

	Ammonium Acetate Extractable Potassium (ppm K)			p-values		
	Top	Middle	Bottom	Top vs. Mid	Top vs. Bot	Mid vs. Bot
Fall 1994	153 (137, 171)	182 (152, 219)	170 (149, 193)	ns	ns	ns
Fall 1995	146 (134, 160)	151 (130, 176)	143 (128, 159)	ns	ns	ns
Fall 1996	171 (154, 191)	190 (156 , 232)	170 (150, 193)	ns	ns	ns

*-Values represent mean (mean less one standard deviation, mean plus one standard deviation) after back-transformations of log-transformed statistics.

#-Values represent mean (standard deviation) for normally distributed statistics.

-Ψ Numbers within a row followed by different letters are significantly different at $p< 0.10$.

Appendix E. Soil Moisture Content at Sample Collection, 1994-2002

Gravimetric % H_2O at Biological Sampling by Management

	MIG	CG	RC
Fall 1994	27.79 (5.26)*	33.29 (7.28)	29.96 (6.58)
Fall 1995	27.63 (5.52)	33.58 (9.08)	29.56 (5.93)
Fall 1996	24.16 (5.90)	27.42 (1.65)	26.10 (6.06)
Fall 2002	31.12 (6.11)	30.91 (1.08)	31.84 (2.77)

Gravimetric % H_2O at Biological Sampling by Landscape Position

	Top	Middle	Bottom
Fall 1994	27.38 (4.34)	24.67 (4.09)	31.91 (6.20)
Fall 1995	26.75 (5.20)	26.74 (4.82)	30.79 (6.59)
Fall 1996	23.04 (4.81)	21.13 (5.74)	28.04 (5.03)
Fall 2002	28.59 (2.47)	29.84 (8.99)	34.12 (5.57)

Gravimetric % H_2O at Physical Sampling by Management

	MIG	CG	RC
Fall 1994	26.24 (4.53)	30.67 (6.00)	29.30 (6.20)
Fall 1995	24.81 (4.29)	28.87 (6.94)	27.17 (6.20)
Fall 1996	21.94 (4.58)	23.50 (2.09)	23.61 (7.10)
Fall 2002	27.98 (4.18)	27.58 (1.06)	30.17 (2.68)

Gravimetric % H_2O at Physical Sampling by Landscape Position

	Top	Middle	Bottom
Fall 1994	25.66 (3.61)	23.88 (4.31)	30.18 (5.17)
Fall 1995	23.41 (2.63)	23.85 (4.40)	28.34 (5.46)
Fall 1996	20.09 (4.43)	21.11 (3.01)	25.04 (4.50)
Fall 2002	26.25 (1.41)	26.25 (6.13)	30.69 (3.73)

*-Values represent mean (standard deviation).