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LONG-TERM CROPPING SYSTEMS EFFECTS ON SOIL AGGREGATE STABILITY, CORN GRAIN YIELDS, AND YIELD STABILITY

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ABSTRACT

The growing awareness regarding the ecological and economic impacts of intensive agriculture has elevated interest in developing sustainable cropping systems that provide high crop productivity, reduce reliance on external inputs, and improve soil quality. Two studies which are described in the five chapters of this thesis, assessed long-term cropping systems effects on soil aggregate stability, corn grain yields, and yield stability in a 36-year-old crop rotation and fertility experiment, named the Hunter Rotation Experiment (HRE).

In the first study, we evaluated long-term effects of ten different crops grown in four cropping systems of HRE on soil aggregate stability, estimated by water-stable aggregates (WSA), during four months of a growing season. Water-stable aggregates depend on temporary binding agents such as roots and fungi which are affected by crop management. Because annual plants support shorter live-root periods, we hypothesized that WSA would be higher in soils under perennials (PR) and double-cropped small grains (SG) than in soils under summer annuals in annual systems (SA_a), and summer annuals in perennial and diverse systems (SA_p). We also hypothesized that WSA would fluctuate more during a growing season in soils under summer annual crops than in soils under PR and SG. Further, the live-root period in a cropping system and soil microbial biomass carbon (SMBC) would predict WSA better than total soil organic carbon and tillage frequency.

We sampled soils of 10 crops from four cropping systems managed under inorganic fertilizers in the HRE: two annual systems: two annual systems: continuous corn (*Zea mays* L.), corn-soybean [*Glycine max* (L) Merr.]; a perennial system: 4yr corn-

4yr alfalfa (*Medicago sativa* L.); and a diverse system: corn-oats (*Avena sativa* L.)/wheat (*Triticum aestivum* L.)-2yr red clover (*Trifolium pratense* L.)+ timothy (*Phleum pratense* L.) in spring, summer and autumn, 2005. We measured % WSA by slaking and wet-sieving the air-dried 1-2 mm aggregates in water.

The WSA under PR, SG and SA_p were respectively 106%, 107%, and 84% higher than under SA_a. The WSA under SA_p did not differ from the WSA under PR and SG, indicating a more pronounced cropping system effect than individual crop-effect. Water-stable aggregates varied more under the summer annual crops than under PR and SG from spring-autumn. Estimated live-root period predicted WSA best along with soil water content and SMBC (R^2= 0.95).

The second study evaluated average corn grain yields, yield trends and yield stability in the four cropping systems under three fertility regimes of the HRE during 1990-2005. We hypothesized that corn yields would be higher, more stable and increase more over time in: i) perennial and diverse cropping systems compared to annual systems, and ii) manure-fertility compared to inorganic-fertility regimes. Fertility regimes were inorganic, or manure based on crop N- or P-needs.

Mean yields in 4C4A and COW2RT were 10-12% higher than CC and 7% higher in 4C4A than CS. Yields increases over time did not differ (0.28 Mg ha^{-1} yr^{-1}) among all treatments. Coefficient of variation (CV) analysis, however, indicated that yield variability was significantly higher in CC (CV = 28%) than in 4C4A (CV = 21%) across fertility regimes.

According to regression stability analysis, response of corn yields to the environmental conditions did not differ among four cropping systems within inorganic and P-based manure fertility. Under N-based manure fertility, however, yields diverged between CC and other systems in the poorest-yielding year but converged in the highest-yielding year. Response of corn yields to the environmental conditions did not differ between manure- and inorganic-fertility, but yields were 7% higher under manure-fertility in the poorest-yielding year.

The results indicate that perennial and diverse cropping systems that rotate corn with perennials and winter double-cropped small grains, can promote higher soil aggregate stability than a corn-soybean or continuous corn system. Compared to CC, perennial and diverse systems are likely to produce higher yields across three fertility regimes, and more stable yields under N-based manure fertility.

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CHAPTER 1

REVIEW OF LITERATURE AND RESEARCH OBJECTIVES

INTRODUCTION

Industrial agriculture based on the principles of specialization and intensification has achieved great success for the past several decades (Kirschenmann, 2002; Kirschenmann, 2007). The increased crop production with technological advancement, however, has come at an environmental cost. For instance, conventional cropping systems involving only annual row crops grown with intensive tillage often degrade soil quality (Varvel, 1994; Karlen et al., 2006). Similarly, reliance on external inputs such as synthetic fertilizers and pesticides has environmental concerns due to leakage to non-intended places such as surface and ground waters (Barbash et al., 2001; Domagalski et al., 2008), and high consumption of energy (Pimentel et al., 2005a). Agriculture faces the challenge to produce enough food for growing populations at an acceptable environmental cost (Robertson and Swinton, 2005; Miller, 2008). The growing awareness regarding the ecological and economic impacts of intensive agriculture has elevated interest in developing sustainable cropping systems that provide high crop productivity, reduce reliance on external inputs, and improve soil quality (e.g. Pimentel et al., 2005b; Smith et al., 2007; Posner et al., 2008).

A large body of research has studied cropping systems effects on soil quality or crop yields, while relatively few studies have studied both together. Understanding how long-term effects of cropping systems on both soil quality and crop yields could help identify and design sustainable cropping systems that provide high and stable yields along with maintaining soil quality.

Two studies that assess cropping systems effects on soil aggregate stability and corn yields and yield stability are described in the five chapters of this thesis. The first chapter reviews the current literature pertaining to soil aggregate stability and crop productivity. Specifically, the first part of this chapter includes a review of research on the effects of crop rotations on soil aggregate stability and the possible mechanisms/factors contributing to the differences among cropping systems. The second part of the first chapter reviews research on crop yields and yield stability.

Chapter two is the manuscript describing the long-term effects of cropping systems on soil aggregate stability that has been submitted to the Soil Science Society of America Journal and is under review. Chapter three is the manuscript describing long-term effects of cropping systems on corn grain yields and yield stability, and will be submitted to the Agronomy Journal. Chapter four describes the general conclusions from the two studies on soil aggregate stability and corn yields and yield stability. Chapter five is an extension publication describing results from previous and this research on various soil quality indicators and corn grain yields and yield stability conducted at the same long-term cropping systems study. This publication is intended for extension educators and the farming community to help farmers identify and design sustainable, productive and profitable cropping systems.

Soil Quality

Soil quality is a broad term indicating overall capacity of a soil to support optimum crop growth and high crop yields and maintain environmental quality (Karlen et al., 1997). It includes physical, chemical and biological indicators. Some examples of the indicators of soil quality are soil aggregate stability, water infiltration, erodibility, soil porosity, pH, CEC, fertility, and microbial and faunal activities. Crop rotations that include perennials as compared to only annual crops, have been reported to increase various indicators of soil quality such as soil aggregate stability, soil organic carbon, microbial biomass C, and water infiltration; and lower bulk density (Tisdall and Oades, 1982; Chaney and Swift 1984; Angers and Mehuys, 1989; Drury et al., 1991; Haynes et al., 1991; Angers et al., 1993; Katsvairo et al., 2002; Karlen et al., 2006; Pikul et al., 2006; Pikul et al. 2007).

Cropping systems effects on soil carbon

Explanations of how agronomic practices affect soil C include the quantity and quality of crop residues of different crops in cropping systems. Various studies have found that the quantity of crop residues returned to the soil was important in maintaining soil C. Havlin et al. (1990) found that compared to continuous soybean, the rotation regimes with a high frequency of sorghum (i.e. sorghum-soybean and sorghum-sorghum) resulted in 10 and 24% more soil organic C, respectively, under conventional tillage; and 30 and 39% more soil organic C, respectively, under no-till conditions.

On the other hand, Drinkwater et al (1998), concluded from their 15-year farming-systems comparative study, that it was the crop type and diversity, not the quantity of the residues added by different cropping systems that affected soil C. A more diverse manure-based system had significantly higher soil organic carbon than a conventional annual cropping system after 15 years of the study, in spite of the fact that both systems had added similar quantities of organic residues. Pikul et al. (2007) also observed a 36% increase in fine particulate organic matter and total soil organic matter content with a 5-yr diverse crop rotation as compared to corn monoculture.

Other researchers, however, have found that quantity as well as quality of the crop residues added to the soil influences the soil C (Varvel, 1994). At low rates of N fertilizer, a diverse rotation of corn-oat+ clover-grain sorghum-soybean (C-OCL—SG-SB) and C-SB-SG-OC had significantly more soil C than the C-C and SG-SG monocultures. However, at economically highest rates of nitrogen fertilizer, the C-C and SG-SG monocultures had similar or more soil carbon as compared to the diverse rotations due to increased residues. By contrast, in another long-term study, continuous corn had similar total soil C as a diverse (corn-oats/wheat/2 yr red clover) and a perennial (4 yr corn-4 yr alfalfa) rotation (Bucher, 2002).

Soil aggregate stability

Soil aggregates are soil particles joined together more strongly than their surrounding particles (Martin et al, 1955). Aggregate stability is the ability of soil particles to resist the disruptive forces of wind and water (Kemper and Rosenau, 1986). Stability of soil aggregates is an important indicator of soil quality as it plays a significant role in improving soil organic carbon storage, pore size distribution, water infiltration, aeration and plant root growth; and reducing soil erosion (Prove et al., 1990; Angers and Caron, 1998; Barthes and Roose, 2002; Lado et al., 2004).

Soil aggregate formation and stabilization

Various theories have been proposed in the literature about how aggregates are formed and stabilized in soil. Edwards and Bremner (1967) proposed the microaggregate theory according to which microaggregates (<250 µm) consist of clay-polyvalent metal-organic matter complexes (Cl-P-OM) which are further joined with similar complexes (Cl-P-OM) to form macroaggregates $[(Cl\text{-}P\text{-}OM)_x]_y$. The authors suggested that microaggregates are more stable than macroaggregates.

Tisdall and Oades (1982) proposed the aggregate hierarchy concept according to which different binding agents act at different hierarchical stages of aggregation. Primary soil particles and smaller microaggregates (<20 µm) are joined together into stable microaggregates (20-250 µm) by persistent binding agents such as humidified organic matter and polyvalent metal cation complexes, oxides and alluminosilicates. These microaggregates unite together to form macroaggregates (>250 µm) via the function of temporary agents such as roots and fungal hyphae, and transient binding agents such as polysaccharides. They further stated that microaggregates are less affected by management than macroaggregates.

Oades (1984) proposed an opposing order of aggregate formation hierarchy and postulated that macroaggregates form first in soil and that microaggregates form around the roots and fungal hyphae contained within macroaggregates. Results from several studies have substantiated this modified theory (e.g. Elliott, 1986; Golchin et al., 1994; Angers et al., 1997; Gale et al., 2000a,b). In another study, Oades and Water (1991) concluded that aggregate hierarchy exists only in soils where organic matter is the dominating binding agent and does not exist in oxide-rich soils where oxides are the major binding agents.

Dexter (1988) offered the ‘principle of porosity exclusion’; according to which larger aggregates have higher porosity than smaller aggregates because they contain pores between the smaller dense aggregates. The larger aggregates are weaker than the smaller aggregates because the former contain larger pores which act as planes of weakness. Further, Kay (1990) proposed that various binding agents act at different aggregate stages depending upon their size and thus physical accessibility to different pore sizes. The small persistent binding agents such as humic material will thus stabilize microaggregates by accessing smaller pores, while roots and fungal hyphae can access larger pores only and will thus stabilize macroaggregates.

It has been reported that the aggregate hierarchy occurs mainly in soils in which organic material is the main binding agent (e.g. Mollisols dominated by 2:1 minerals) but not in soils dominated by oxides (e.g. Oxisols with 1:1 type clay mineralogy) where oxides or electrostatic interactions are the main binding agents (Oades and Waters, 1991; Six et al., 2000; Denef and Six, 2005).

Soil aggregates have been classified into two categories: macro (>250 µm) and microaggregates (<250 µm) and this classification holds true for practical consideration (Edwards and Bremer, 1967; Tisdall and Oades, 1982). Microaggregates are relatively stable and less sensitive to management practices (Edwards and Bremer, 1967). The stability of macroaggregates may depend upon the management practices such as crop rotation and tillage, and thus soil organic matter level, except in highly weathered soils dominated by 1:1 clay minerals, in which Al- and Fe-oxides unite particles into macroaggregates (Six et al 2000). Aggregate stability as discussed in this review will refer to stability of aggregates to wetting disintegrative forces of water, thus described as water stable aggregates (WSA) [Amezketa, 1999].

Cropping systems effects on soil aggregate stability

Cropping systems significantly influence aggregate stability of soils. Perennial and diverse cropping systems have been found to improve aggregate stability as compared to annual row crop based cropping systems (e.g. Rachman et al., 2003). Peters et al. (1997) reported the highest WSA in soils of a farming system in which green manure, hay or small grain crops were present in winter in addition to summer crops. These systems maintained live plant cover (and hence live roots) for a longer period than a corn-soybean system that did not include living plants during the winter months.

Similarly, inclusion of cover crops in the rotation can enhance soil organic matter, biological activity and thus soil aggregate stability by providing live roots during an otherwise fallow period. Winter cover crops of rye, oats and their combination significantly enhanced fungal hyphal length and aggregate stability as compared to a winter fallow (Kabir and Koide, 2002). Similarly, in another study, cover crops of fall rye and annual ryegrass resulted in significantly higher aggregate stability measured as mean weight diameter of aggregates as compared to a bare fallow treatment (Liu et al., 2005). Villamil et al., (2006) also reported up to 17% increase in WSA by including winter cover crops in a no-till corn-soybean system.

Cropping systems affect soil aggregate stability due to various factors such as type of crops, sequence of crops, intensity of cropping, crop and soil management techniques (Tisdall and Oades, 1980; Elliott, 1986; Karlen et al, 2006; Villamil et al., 2006; Pikul et al., 2007). These factors can affect soil aggregate stability directly or indirectly by modifying other related soil characteristics.

Crop effects

Crops differ in their ability to influence aggregate stability and related characteristics of soil, depending upon the quantity and quality of residues left on the soil, and their rooting patterns and activities (Martens, 2000; Power et al., 1998). Perennial crops have been found to enhance soil aggregation as compared to annual crops (Tisdall and Oades, 1980; Stone and Buttery, 1989; Rachman et al., 2003), which appears to be due to higher root contributions and associated microbial activity. In a study comparing annual and perennial crops, Drury et al. (1991) recorded significantly higher soil microbial biomass C and wet aggregate stability in soils under perennial crops of reed canary grass and alfalfa than under annual crops of corn and soybean at different sampling dates from June to September. The authors attributed the increases in microbial activity and WAS under perennials to their increased root exudates and C inputs.

Perfect et al. (1990) compared WSA under six perennial forages established two years previously and conventional and zero-till corn. They sampled at different periods during a growing season. They found a significant increase in WSA under all the forages as compared to the corn treatments. In another study, Stone and Buttery (1989) compared the effect of many grass and legume forages in a growth chamber study. They observed highest root growth and aggregate stability under reed canary grass after 80 days of growth.

Perennial crops also result in less disturbed ecosystems due to reduced frequency of cultivation, thus directly reducing mechanical disturbance of soil (Elliott, 1986) and benefiting microorganisms such as mycorrhizae fungi which further promote soil aggregation. For example, Jastrow (1987) found that restoration of land under cultivated corn to prairies caused significant increase in percent stable macroaggregates associated with increased root and fungal growth as compared to the land retained under cultivated corn.

Tisdall and Oades (1980) studied stability of macroaggregates as affected by various 50-year crop rotations including fallow, annual crops of wheat, pastures, and native virgin land. They observed that cultivation significantly reduced macroaggregate stability as compared to the virgin land. They concluded that macroaggregation can be restored by growing crops with extensive root systems and minimum cultivation such as pastures of rye grass.

Thus crop rotations influence soil aggregation because of the crop related factors and their associated management practices. It has been found that particulate organic matter (POM), which consists of plant residues, is abundant in water stable macroaggregates, and that this POM may be central in macroaggregate formation and stabilization (Golchin et al., 1994). Thus an input of organic residues is an important factor for soil aggregation and stabilization.

Plant roots

Plant roots promote soil aggregate stability by acting as temporary binding agents via various processes such as physical enmeshment of soil particles, penetration and anchorage of soil, release of soil-binding exudates, supply of organic residues, and change in soil water regime (Tisdall and Oades, 1982; Miller and Jastrow, 1990; Chantigny et al., 1997; Angers and Caron, 1998; Jastrow et al., 1998). Aggregate stability is greater in rhizosphere soil than in bulk soil (Caravaca et al., 2002). Reid and Goss (1981) proposed that root growth may be the major factor controlling magnitude of aggregate stability under arable crops.

Roots often promote formation and stabilization of macroaggregates by enmeshing soil particles. Miller and Jastrow (1990) observed that root length, the lengths of roots colonized by mycorrhizal fungi, and hyphal lengths of mycorrhizal fungi were all highly correlated with soil aggregate stability measured as geometric mean diameter of water-stable aggregates in a restored prairie soil. In another study from the same experiment, Jastrow et al. (1998) further observed that the restoration of macroaggregate structure was driven by the direct and indirect effects of roots and fungal hyphae.

Roots supply organic C to the soil through normal growth and senescence of root segments and hairs. They also release organic materials and thus enhance the microbial activity in soil which furthers the release of organic binding agents quantified and described as hot water-extractable carbohydrates (Lynch and Whipps, 1991). Root mucilage may also promote stability of aggregates by increasing bond strength and reducing wetting rate (Czarnes et al., 2000). Baldock and Kay (1987) observed that roots promote stable aggregates through exudation of material such as polysaccharides.

Decomposing roots also promote aggregate stability (Puget and Drinkwater, 2001; Gale et al., 2000a,b). Root derived carbon promotes WSA because of its continuous supply and high retention as occluded particulate organic matter (POM)-carbon in soil aggregates (Gale et al. 2000a, b; Puget and Drinkwater, 2001). Gale et al (2000a) found that root derived intra-aggregate particulate organic matter (POM) was more important than surface residue C in stabilization of small macroaggregates (250-2000 μm) under simulated no-till conditions. They emphasized the importance of plant roots and root exudates in the formation of stable macroaggregates in relatively undisturbed systems like no-till. The amount of organic C supplied by roots depends upon their mass and length (Shamoot et al., 1968); roots with greatest mass often contribute to the greatest increases in soil aggregation (Stone and Buttery, 1989).

Root penetration also induces loosening and fragmentation of soil; it decreases proportion of relatively unstable macroaggregates and increases the proportion of relatively stable microaggregates (Materechera et al., 1994). Roots can also increase aggregate stability via water uptake from soil causing a localized drying of soil and adsorption of root exudates on soil particles (Reid and Goss, 1982).

Soil microorganisms

Soil microorganisms such as bacteria and fungi promote soil aggregation by acting as temporary binding agents (Tisdall and Oades, 1982; Gupta and Germida, 1988; Jastrow et al., 1998). Soil microbial biomass has been found positively correlated with WSA (Gupta and Germida, 1988; Carter, 1992). Drury et al. (1991) found higher soil microbial biomass C (MBC) and WSA under reed canarygrass and alfalfa than under continuous corn and soybean at different sampling dates from June to September. They found that WSA was significantly related with the MBC at all the sampling dates. Bacteria mainly play a role in the stabilization of microaggregates by producing mucliages (Oades, 1993), while fungi may be more important for stabilizing macroaggregates (Tisdall and Oades, 1982; Schutter and Dick, 2002).

Fungal hyphae enhance soil aggregate stability through physical enmeshment effects and release of mucilages (Tisdall and Oades, 1982; Haynes and Beare, 1995;

Miller and Jastrow; Jastrow et al., 1998). Fungal hyphae networks entangle soil particles and further unite them together producing polysaccharides, a phenomenon, described as the ‘sticky string bag’ effect (Oades and Waters, 1991; Tisdall et al., 1997). Arbuscular mycorrhizal fungi produce an insoluble glycoprotein, called glomalin, which has been linked to the soil aggregate stabilization effect of mycorrhizal fungi (Wright and Upadhaya, 1998; Rillig et al., 2002). The concentration of glomalin in soil has been reported to be higher under perennial grasses as compared to annual crops (Wright et al., 1999; Wright and Anderson, 2000).

Soil fauna

Soil fauna, such as earthworms and other insect larvae enhance soil aggregation by processing the soil through their digestive systems. During digestion, the soil is mixed with humified organic material and then released as casts or pellets (Tisdall and Oades, 1982; Lee and Foster, 1991). Higher abundance of earthworms has been positively correlated with increased soil aggregate stability (Marinissen, 1994; Blanchart et al., 1997; Ketterings et al., 1997). Compared with annual crop rotations, perennial based crop rotations have also been reported to result in less destruction of soil animals such as earthworms and to have higher availability of plant food for increasing soil animal populations (Jordan et al., 1997; Katsvairo et al., 2002). Pulleman et al (2005) found higher number of stable aggregates in form of earthworm castings under a permanent pasture as compared to a conventional system of arable crops.

Soil disturbance

Soil disturbance due to tillage can affect aggregate stability directly by destroying the aggregates and indirectly by enhancing the organic matter decomposition (Elliott, 1986; McVay et al., 2006; Blanco-Canqui et al., 2007).

Zotarelli et al. (2005) studied impacts of tillage and crop rotation on stability of macroaggregates and aggregate associated C & N in two oxisols. They observed that mean weight diameter (MWD) of the aggregates was greater (by 0.5 mm) under no-till (NT) than under conventional tillage (CT). They recorded a 10% decrease in proportion of macroaggregates (> 2mm) and a corresponding increase in microaggregates under CT as compared to NT.

Similarly in another study, Wright and Hons (2004) also found that NT increased aggregation and proportion of macroaggregates more than conventional tillage (CT). They also found that NT increased soil organic carbon (SOC) in macroaggregates by 158% while in microaggregates by only 40% at 0-5 cm soil depth.

Tillage reduces aggregate stability by also adversely affecting soil microorganisms such as fungi that are involved in stabilizing aggregates. Fungi have been reported to be enhanced in less disturbed soils under conservation tillage and less intensive cropping systems, as compared to conventional tillage and intensive monocultures (Guggenberger et al., 1999; Oehl et al., 2003). Wright et al. (1999) reported greater concentration of glomalin, a soil-binding glycoprotein produced by arbuscular mycorrhizae, in a soil under no-till corn as compared to a plowed corn soil.

The adverse effects of tillage on aggregate stability, however, may be reduced by increasing presence of live roots for long periods, for instance, by including winter cover crops in the cropping systems (Liu et al., 2005).

Soil organic carbon

Soil organic carbon has been reported to significantly influence aggregate stability

(Tisdall and Oades, 1980; Tisdall and Oades, 1982). Results, however, differ in the literature regarding the role of total SOC in increasing soil aggregation under different cropping systems. Many researchers have found a strong relationship between soil aggregate stability and total SOC (Tisdall and Oades, 1980; Chaney and Swift, 1984; McVay et al., 2006; Pikul et al., 2007). For instance, Kong et al. (2005) assessed aggregate stability and SOC retention under 10 cropping systems. They found that aggregate stability increased linearly with amounts of C inputs (r^2 =0.75, p=0.001) and SOC (r^2 =0.63, p=0.006).

In contrast, others have found that it is the active fraction or labile pools of soil carbon such as water extractable soil carbohydrates, microbial biomass carbon, root exudates and mucilages, that most affect the soil aggregate stability (Carter et al., 1994; Golchin et al., 1995). Oades (1967) found that aggregate stability is related better to free organic material than to total organic carbon because this fraction acts as substrate for microbes producing the glues and this fraction is a measure of roots and fungal hyphae. Golchin et al (1994) also concluded that it is mainly active or young organic matter that is involved in stabilizing soil aggregates.

Similarly, Carter et al (1994) observed significant differences in WSA of soils under three different cool-season perennials grasses. However, they did not find any significant differences in level of total organic carbon in soils under these grasses. They concluded that WSA was not related to total soil organic carbon but to water extractable carbohydrate carbon content.

In another study, Boix-Fayos et al. (2001) found that stability of macroaggregates was positively correlated with organic matter content above a threshold level, below which it was more strongly correlated with carbonate content. Soil organic matter is the main binding agent in formation of macroaggregates in moderately weathered soils dominated by 2:1 clays whereas in highly weathered soils dominated by 1:1 clay minerals, aggregate formation is mediated by oxides (Six et al., 2000; Denef and Six, 2005)

Soil water content

Water content of a soil can also influence its aggregate stability. Aggregate stability may increase with drying of soil as the reducing water level increases the pull between soil particles by increasing the contact points; and because organic materials, silica and $CaCO_3$ become more concentrated with drying thus making the bonds between soil particles stronger (Kemper and Rosenau, 1986).

Soil aggregate stability under crop phases

Most researchers have studied aggregate stability of cropping systems by comparing soils of only one individual crop of a cropping sequence (e.g. Chaney and Swift, 1984; Angers and Mehuys, 1989; Haynes et al., 1991; Angers et al., 1993; Bucher, 2002; Wright and Hons, 2004; Kong et al., 2005). Bucher (2002) measured soil aggregate stability and other related properties only once in the growing season (spring) in only the corn phase of the cropping systems of a long-term crop rotation and fertility study.

Others have compared individual crop species grown without rotation (e.g. Drury et al., 1991; Chantigny et al., 1997). Information is lacking on how crop phases, the individual crops in a cropping sequence, affect soil aggregate stability and whether it varies among crop phases that differ in root growth and microbial biomass C, and soil disturbance (Elliott, 1986; Chantigny et al., 1997; Jastrow et al., 1998).

Some studies have found differences in soil aggregate stability under different crop phases (Martens, 2000; Villamil et al., 2006). For instance, Martens (2000) found lower WSA in soil after soybean than after corn in a corn-soybean rotation.

Seasonal changes in aggregate stability

There is also evidence that the effect of crops on aggregate stability and related soil characteristics such as microbial biomass carbon can vary within a growing season (Baldock and Kay, 1987; Perfect et al., 1990a, b; Drury et al., 1991; Angers et al., 1993). For instance, Perfect et al. (1990a) found significant temporal variation in root length and weight of different forages and corn during a growing season, and they suggested that this variation might influence the soil aggregate stability. They observed highest growth of perennial grass roots during spring, while corn root growth was highest during late summer, and root growth of perennial legumes was relatively uniform over the growing season.

Drury et al. (1991) found higher soil microbial biomass C and WSA under reed canarygrass and alfalfa than under continuous corn and soybean at all four sampling dates from June to September. The authors attributed these differences to corresponding higher root exudates and C inputs. Pikul et al. (2006) reported temporal variations in aggregate stability and suggested that aggregate stability should be studied at multiple times during a growing season.

Methods for measuring soil aggregate stability

Several methods have been reported in the literature for measuring water stability of macroaggregates. A stability test consists of applying a disintegrative force in the form of wet-sieving to a known weight of air-dried or field-moist and then rewetted soil samples. The amount of soil retained on the sieve is recorded as a measure of the stable portion. The important divergence among different methods has been reported in pre-treatment of the samples. The pre-treatment involves: i) air-drying or keeping the soil field moist and ii) rewetting by immersion (slaking-fast wetting) or misting or capillary (slow rewetting).

Air-drying vs field moist pre-treatment

Many researchers have found that soil samples maintained at field-moist conditions were better than air-dried samples for detecting differences in the effect of cropping practices on water stable aggregates (Perfect et al., 1990; Pojasok and Kay, 1990; Beare and Bruce, 1993).

Other workers, in contrast, have emphasized the importance of air-drying the soil samples to bring all the samples at uniform moisture content for standardization of initial conditions prior to stability measurements (Kemper and Rosenau, 1986; Amezketa et al., 1996; Amezketa, 1999). The variability in initial soil water content at the time of sampling can affect the measurements of aggregate stability and, therefore, can confound the effect of management practices on aggregate stability when using field moist samples for the measurements.

Several researchers have used the air-drying method for studying aggregate stability (Kemper & Rosenau, 1986; Oades and Waters, 1991; Elliott, 1986; Amezketa et al., 1996; Rillig et al, 2002; Rachman et al., 2003). Kemper and Rosenau (1986), however, recommended that long storage of air-dried samples before analysis should be avoided because over time aggregate stability can slowly increase as the reducing water level increases the pull between soil particles by increasing the contact points, and also because organic materials, silica and $CaCO_3$ become more concentrated with drying thus making the bonds between soil particles stronger.

Slaking (fast-wetting) vs capillary wetting or tension wetting (slow-wetting)

The rate of re-wetting of the soil samples before sieving has also been found to affect aggregate stability measurements. Rapid wetting of air-dried aggregates by immersion in water can rupture them due to sudden release of entrapped air and displacement of O_2 and N_2 gas molecules by water (Kemper et al., 1984; Kemper and Rosenau, 1986). Slow wetting has been proposed for studying aggregate stability which can be achieved by humidifying the soil samples (Kemper and Rosenau, 1986) or by tension wetting or capillary wetting (Beare and Bruce, 1983), because fast wetting by immersion may cause a sudden burst of aggregates thus making it difficult to separate the effect of disruptive force of wet-sieving.

Other researchers, however, have found the slaking treatment of air-dried aggregates better than misting for detecting differences of management practices on aggregate stability. For example, Elliott (1986) studied soil aggregate size distribution under conventionally tilled wheat-fallow system and a native sod. He found no significant differences in aggregate size distributions between soils of two systems when using misting method for rewetting the air-dried samples. However he was able to detect significant differences between aggregate size distributions of soils under the two systems when he used the slaking method of re-wetting of the samples.

Eviner & Chapin (2002) studied aggregate stability under different plant species of grassland in California. They argued that slaking resistance of the aggregates is the best indicator of aggregate stability because it mimics the drying-wetting cycles experienced in the grassland.

Slaking of soil aggregates by rapid immersion is also representative of flooding with irrigation or heavy rainfall (Kemper and Rosenau, 1986). Yoder (1936) proposed that slaking resistance is one of the most important properties of soils in relation to erosion control. Kemper and Rosenau (1986) also reported that air-drying slaking method is particularly appropriate for studying soils with relatively high aggregate stabilities such as in humid regions.

In addition to their effects on soil quality, as discussed in the preceding section, cropping systems have also been shown to influence crop yields.

Crop Yields

Cropping systems are known to influence crop yields (Karlen et al., 1994). Several studies have reported higher mean grain yields of corn rotated with perennial and diverse crops as compared to corn monoculture or annual crop rotations (Porter et al., 2003; Stanger et al., 2005; Posner et al., 2008). For instance, Howard et al (1998) reported that corn-soybean rotation increased the corn and soybean yields by 14% and 11% over their monocultures, respectively. Similarly, Pederson and Lauer (2002) found an 8-12% increase in corn and soybean grain yields with corn-soybean rotation compared to their monocultures.

Sumner et al. (1990) described yield reductions due to monocultures as compared to diverse crop rotations as “monoculture yield declines”. Porter et al. (1997b) concluded that the closely related grasses (sorghum, sudan grass) were relatively ineffective rotation crops for corn. By contrast, leguminous alfalfa and non leguminous sunflower were equally effective in alleviating a corn monoculture yield depression (17-19% with 1 yr, 22% yield increase with 2 yr interruption with both alfalfa and sunflower). Stanger et al. (2008) reported yield advantages of perennial cropping systems over corn monoculture of up to 54%.

Rotation effect

The yield advantages of crop rotations over monocultures have been described as the “rotation effect” (Pierce and Rice, 1988) and attributed to multiple factors including reduced pest infestations (Howard et al., 1998; Larkin and Honeycutt, 2006; Smith and Gross, 2006); improved crop resource use efficiency (Anderson, 2005; Tanaka et al., 2005); and improved soil quality (Karlen et al., 2006; Russel et al., 2006; Pikul et al., 2007).

Howard et al. (1998) reported a decrease in cyst nematode infestation of soybean rotated with corn as compared to its monoculture. Larkin and Honeycutt (2006) observed higher beneficial microbial activity in soils under several crop rotations than under continuous potato (*Solanum tuberosum* L.). They also observed that the soil under continuous potato also had greater soilborne diseases as compared to the soil under crop rotations.

Diversification of crop rotations with certain crops has also been shown to increase crop yields by increasing water use efficiency (Anderson, 2005). For instance, Tanaka et al., (2005) observed that including a dicot crop in rotation with winter wheat (winter wheat-corn-dry pea) increased water-use efficiency of winter wheat by 56% and its yield by 76% as compared to its rotation with only monocots (winter wheat-corn-proso millet).

In addition to the improved physical soil quality benefits of perennial and diverse cropping systems, as discussed earlier, improvements in cycling and availability of nutrients are also associated with the yield benefits of these cropping systems over monocultures. Rotating corn with perennial legume crops such as alfalfa has been reported to yield higher than corn monoculture even in the presence of N fertilizers applied at variable rates (Russell et al., 2006; Stanger et al., 2008).

Pikul et al (2005) also compared corn yields under continuous corn (CC), corn-soybean (CS), and corn-soybean-wheat-alfalfa (CSWA) rotations at three rates of nitrogen application. Average corn yields over nine years with zero nitrogen fertilizer were 107 and 61% higher in CSWA and CS rotation than in CC, respectively. Authors attributed yield increases with legumes in the rotation to the increased N mineralization rates and N use efficiency. Similarly, in addition to their N contributions, legume cover crops have also been shown to increase yields, when grown in rotation with annual row crops (Riedell et al., 1998; Singer and Cox, 1998; Vyn et al., 2000).

Yield trends

Changes in crop yields over time are referred to as yield trends and are an outcome of complex factors such as technology, management, and environment. Positive corn yield trends have been observed for several decades in the U.S. (Nielson, 2006). There are reports, however, that the yield trends are increasing at a faster rate since mid-1990s than earlier periods. For instance, the National annual yield increase during 1990-2005 was 0.15 Mg ha^{-1} yr^{-1} (USDA-NASS, 2008).

These higher yield increases since the mid-1990s as compared to earlier periods could be due to several factors including improved seed genetics, better technology, and more favorable environment. Tannura et al. (2008), however, advised caution against popular perception of attributing these yield increases to only seed genetics advancements and transgenic traits. They suggested that favorable environment might have played a larger role than technology for higher yield trends in Iowa, Indiana, and Illinois in a long-term yield analysis.

Yield variability

Crop yields can fluctuate greatly from year-to-year due to variability in environment, pest pressures and management (Varvel, 2000; Wilhelm and Wortmann, 2004; Mallory and Porter, 2007; Posner et al., 2008). Understanding the temporal variability of crop yields has implications for sustainable crop production particularly in light of the changes projected due to global climate change (Wetherald and Manabe, 1995; Dai et al., 2001; Weiss and Bradley, 2001; Pathak et al., 2003). Evaluation of crop yields, therefore, should include two indicators- yields and stability of yields across variable climatic conditions (Swift, 1994).

Long-term studies are particularly valuable for studying yield stability among cropping systems (Raun et al., 1993; Mallory and Porter, 2007; Smith et al., 2007). Perennial and diverse cropping systems have been found to have higher yields across variable environments. Varvel (2000) reported higher and less variable crop yields in two- and four-year rotations compared to monocultures of corn, sorghum and soybean in a 16-yr study.

Yield advantages of crop rotations are often greater during stress conditions than during normal environments. Wilhelm and Wortmann (2004) studied the influence of seasonal temperature, precipitation, primary tillage, and crop rotation on rainfed corn and soybean production over 16 yr in the southeastern Nebraska. They found that corn and soybean produced less grain with high summer temperatures. Corn yield increased with less than normal spring rainfall, and more than normal summer rainfall. Grain yield was greater with rotation than continuous cropping for both corn (7.10 vs. 5.83Mg ha^{-1}) and soybean (2.57 vs. 2.35 Mg ha^{-1}), and the benefit of rotation was greatest for corn during the low-yielding years.

In three long-term studies in the northern Corn Belt, Porter et al. (1997a) found that corn rotated with soybean yielded more than its monoculture. The relative increase in yields in annual rotation compared with monoculture was approximately twofold greater in low-yielding than in high-yielding environments. In low-yielding environments, the yield advantage of an annual rotation of corn and soybean compared with monoculture was frequently greater than 25%.

Hu and Buyanovsky (2003) studied corn grain yields and climatic data for a period of 104 years in Missouri and found that high-yielding years had less rainfall and warmer temperatures during the planting period, more rainfall and warmer temperatures during germination and emergence, and more rainfall and cooler-than-average temperatures in the anthesis and kernel-filling periods from June through August.

Manure vs synthetic fertilizers effects

Fertility management practices such as addition of manure can also influence stability of crop yields. Cropping systems managed with organic amendments such as animal manure have been shown to produce higher crop yields under stress conditions and reduce yield variability as compared to systems fertilized with inorganic fertilizers. Lotter et al. (2003) reported that a long-term diverse and organic farming system treatment managed with animal manure yielded significantly higher corn yields than a conventional inorganically fertilized annual rotation during a severe drought year in Pennsylvania. They attributed the yield advantage of manure treatments over inorganic fertilizer treatments to the improved water holding capacity of soil under manure.

Similarly, Mallory and Porter (2007) also observed more stable potato yields in an amended soil system (manure, green manure, compost and supplemental fertilizer) as compared to a contrasting non-amended soil system (synthetic fertilizers). They linked the yield stability advantages of amended systems over non-amended systems during years with limited rainfall as due to the increased resilience of soils due to improved aggregate stability, organic carbon, cation exchange capacity, and nutrient status of soil. Some studies found no advantage of improved soil quality with manure-amended systems on yield stability (Aref and Wander, 1998; Eghball et al., 1995), while others have reported greater yield variability in organic amended systems than in inorganic systems (Clark et al., 1999).

Yield stability analysis

Year-to-year variability in yields is often detected using the conventional ANOVA as a significant interaction of year x cropping system. This interaction can be difficult to explain in long-term studies. Several techniques have been reported and reviewed to interpret variability or stability of yields (Finlay and Wilkinson, 1963; Eberhart and Russell, 1966; Shukla, 1972; Lin et al., 1986; Kang, 1993).

Regression stability analysis is an effective technique to visually interpret year-by-cropping system interactions (Hilderband, 1984). This technique was used to interpret genotype-by-environment interactions in plant breeding research (Yates and Cocharan, 1938), and has been extended to management studies (e.g. Hildebrand, 1984; Raun et al., 1993; Boman et al., 1997). With this technique, treatment yield is linearly regressed on an environmental means, which is calculated as the annual mean yield of all the treatments being compared in the experiment (Eberhart and Russell, 1966).

When environment means are ranked from the poorest to the highest yields, they produce a quantitative environment index representing the variable environmental conditions occurring during the study irrespective of the cause of the variability (Eberhart and Russell, 1966; Hildebrand, 1984). The regression lines of treatment yields on the environment index are then compared among cropping systems.

The regression stability assumes that fluctuation in treatment yields over years is caused by environmental factors such as rainfall, stresses, pest pressures and so forth, and is not caused by management (such as soil acidity buildup due to continuous nutrient applications).

Treatments yields may continuously increase or decrease over the years due to some management factors as demonstrated by Guertel et al. (1994). They found that a decreasing trend of yields over the years due to soil acidity built up due to continuous P application. This confounded the yield fluctuations caused solely by environmental variability which was the focus of study. In such situations, the conventional stability analysis could lead to erroneous conclusions and thus should be avoided (Guertel et al., 1994). Coefficient of variation is another common parameter that has been used for comparing year-to-year yield variability in management studies (Lin et al., 1986; Mallory and Porter, 2007; Smith et al., 2007).

Most long-term studies compare average crop yields and do not describe yield stability among cropping systems and few studies have studied year-to-year variability among cropping systems typical of Northeast. In addition to crop yields, yield stability is a valuable parameter to identify cropping systems that produce consistently high yields across variable environments.

A large body of research on cropping systems has focused either on soil characteristics or crop productivity, while fewer studies have analyzed both. Evaluating cropping systems effects on soil quality as well as crop yields and yield stability can help design sustainable cropping systems. In the present study, we aimed at understanding the long-term effects of different crops grown in four cropping systems on soil aggregate stability, corn grain yields, yield trends, and yield stability in a cropping systems experiment established at the Pennsylvania State University R.E. Larson Research Center, Rock Springs, PA.

OBJECTIVES AND HYPOTHESES

The specific objectives and hypotheses of this research were:

Objective 1. Study soil aggregate stability in different seasons of a year under 10 crops including summer annuals, double-cropped small grains, and perennials in four cropping systems managed under inorganic fertility in a long-term experiment.

Hypotheses:

1.1 Water-stable aggregates would be higher in soils under perennials (PR) and double-cropped small grains (SG) than in soils under summer annuals in annual systems (SA_a), and summer annuals in perennial and diverse systems (SA_p).

1.2 Water-stable aggregates would fluctuate during a growing season more in soils under

SA_a and SA_p than in soils under PR and SG.

Objective 2. Evaluate relative significance of presence of live roots, soil disturbance, and soil characteristics including soil organic carbon, microbial biomass carbon, soil water content, and soil matric potential in influencing soil aggregate stability.

Hypotheses:

2.1 The live-root period in a cropping system and soil microbial biomass carbon (SMBC) would predict WSA better than total soil organic carbon and tillage frequency.

Objective 3. Evaluate corn grain yields, yield trends, and yield stability in four cropping systems managed under manure and inorganic fertility regimes.

Hypotheses:

3.1 Corn grain yields would be higher, more stable and increase more over time in : i) perennial and diverse cropping systems compared to annual systems, and ii) manure-fertility compared to inorganic-fertility regimes.

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CHAPTER 2

WATER-STABLE AGGREGATES IN SOILS UNDER FOUR LONG-TERM CROPPING SYSTEMS

ABSTRACT

Water-stable aggregates (WSA) [>250 µm], an important soil quality indicator, depend on temporary binding agents such as roots and fungi which are affected by crop management. Because annual plants support shorter live-root periods, we hypothesized that WSA would be higher in soils under perennials (PR) and double-cropped small grains (SG) than in soils under summer annuals in annual systems (SA_a), and summer annuals in perennial and diverse systems (SA_p). Further, the live-root period in a cropping system and soil microbial biomass carbon (SMBC) would predict WSA better than total soil organic carbon and tillage frequency. We sampled soils of 10 crops from four 36-year-old systems: two annual systems: continuous corn (*Zea mays* L.), corn-soybean [*Glycine max* (L) Merr.]; a perennial system: 4yr corn-4yr alfalfa (*Medicago sativa* L.); and a diverse system: corn-oats (*Avena sativa* L.)/ wheat (*Triticum aestivum* L.)-2yr red clover (*Trifolium pratense* L.)+ timothy (*Phleum pratense* L.) in spring, summer and autumn, 2005. We measured % WSA by wet-sieving the air-dried and slaked 1-2 mm aggregates in water. The WSA under PR, SG and SA_p were respectively 106%, 107%, and 84% higher than under SA_a. The WSA under SA_p did not differ significantly from the WSA under PR and SG, indicating a more pronounced cropping system effect than individual crop-effect. Water-stable aggregates varied more under SA_a and SA_p than under PR and SG from spring-autumn. Estimated live-root period predicted WSA best along with soil water content and SMBC (R^2= 0.95). Results suggest that cropping systems with longer live-root periods can promote WSA with time.

Abbreviations

ANCOVA, analysis of covariance; ANOVA, analysis of variance; 4A, yr 4 alfalfa; 4C, yr 4 corn; 4C-4A, 4 yr corn followed by 4 yr alfalfa; C-C, continuous corn; C-S, corn-soybean; C-O/W-2RT, corn-oats double-cropped with winter wheat-2 years of red clover+ timothy; CC, continuous corn; Cd, corn in diverse system; CS, corn following soybean; SC, soybean following corn; CSPLR, cropping system proportion of time with live roots; CSPT, cropping system proportion of time with tillage; LOI, loss-on-ignition; O, oats; PLSR, partial-least squares regression; POM, particulate organic matter; PR, perennial crops; RT1, yr 1 red clover; RT2, yr 2 red clover; SA_a, summer annual crops in annual systems; SA_p, summer annual crops in perennial and diverse systems; SG, double-cropped small grain crops; SMBC, soil microbial biomass carbon; SOC, total soil organic carbon; SWC, soil water content; SWP, soil water matric potential; WSA, water-stable aggregates; W, wheat;

Growing concerns regarding adverse effects of intensive crop management on soil quality have kindled an interest in identifying cropping systems that maintain desirable soil quality indicators along with high productivity. Aggregate stability is an important indicator of soil quality as it plays a significant role in improving soil organic carbon storage, pore size distribution, water infiltration, aeration and plant root growth; and reducing soil erosion (Prove et al., 1990; Angers and Caron, 1998; Barthes and Roose, 2002; Lado et al., 2004). The water-stability of microaggregates (<250 µm) is mainly influenced by persistent organic binding agents and seems to be less affected by management such as cropping systems (Tisdall and Oades, 1982). In contrast, water-stability of macroaggregates (>250 µm) depends upon temporary binding agents such as plant roots and fungal hyphae, and can be affected by management (Tisdall and Oades, 1982; Beare and Bruce, 1993).

Considerable research has been done on how cropping systems affect water-stability of aggregates (Tisdall and Oades, 1980; Haynes et al., 1991; Angers et al., 1993; Karlen et al., 2006; Pikul et al., 2007). Most researchers, however, have compared cropping systems by comparing WSA in soils of only one crop (e.g. Fahad et al., 1982; Wright and Hons, 2004; Kong et al., 2005). Others have compared WSA in soils under individual crop species grown in monoculture (e.g. Drury et al., 1991; Chantigny et al., 1997). There is little information on the effect of individual crops of cropping systems on WSA, although WSA may vary among soils under individual crop phases because the crops (e.g. annual vs. perennial) differ in root growth, soil microbial biomass, and soil disturbance (Elliott, 1986; Drury et al., 1991; Chantigny et al., 1997; Jastrow et al., 1998; Rachman et al., 2003). Furthermore, there is evidence that the effect of different crops on

WSA can vary significantly within a growing season (Perfect et al., 1990a, b; Drury et al., 1991). Pikul et al. (2006) found significant temporal variation in WSA and recommended avoiding conclusions based on a single point-in-time observation.

The relative significance of factors that promote WSA is also of interest. Several authors have reviewed and reported diverse mechanisms functioning at various hierarchical levels of soil aggregation (Edwards and Bremner, 1967; Tisdale and Oades, 1982; Amezketa, 1999; Six et al., 2004; Bronick and Lal, 2005). Results, however, differ regarding the role that factors such as total soil organic carbon (SOC), SMBC and soil water content (SWC) play in promoting WSA. For instance, many researchers have reported a strong relationship between WSA and SOC (Chaney and Swift, 1984; Kong et al., 2005; McVay et al., 2006; Pikul et al., 2007). In contrast, others have found that it is not the SOC, but the active fraction or labile pools of soil carbon such as water extractable soil carbohydrates, SMBC, root exudates and mucilages that promote WSA (Carter et al., 1994; Golchin et al., 1995). Results also differ regarding the relationship between SWC and WSA (Kemper and Rosenau, 1986, Perfect et al., 1990a, b).

Cropping systems can influence WSA via their effect on plant roots and soil disturbance. Reid and Goss (1981) proposed that root growth may be the major factor controlling the magnitude of WSA in soils under arable crops. Roots enhance WSA in soil by many direct and indirect effects such as physical enmeshment of soil particles, penetration and anchorage of soil, release of soil-binding exudates, and supply of organic residues (Tisdall and Oades, 1980; Reid and Goss, 1982; Miller and Jastrow, 1990; Jastrow et al., 1998). Soil disturbance due to tillage also affects water-stability of aggregates by breaking down aggregates, enhancing organic matter decomposition, and affecting microorganisms such as fungi involved in stabilizing aggregates (Elliott, 1986; McVay et al., 2006; Blanco-Canqui et al., 2007; Pikul et al., 2007). For instance, Wright et al. (1999) found a significantly greater concentration of glomalin, a soil-binding glycoprotein produced by arbuscular mycorrhizae, in a soil under no-till corn as compared to a plowed corn soil.

We initiated this study to investigate how WSA differed in soils under 10 crops of four long-term cropping systems during the growing season. Among the four cropping systems, we hypothesized that perennials (PR) and double-cropped small grains (SG) would promote greater WSA in soil because of longer periods of live-root activity, and less soil disturbance due to tillage (in PR) than SA_a and SA_p. In addition, we expected that the changes in WSA from spring-summer (May-Aug.) and summer-autumn (Aug.-Nov.) would be greater in soils under SA than in soils under SG which in turn would be greater than changes in WSA in soils under PR due to concurrent changes in the presence of live roots of these crops. We also hypothesized that the period of live-root activity for a cropping system would predict WSA better than the tillage frequency. Finally, we hypothesized that the period of live-root activity and SMBC would predict WSA better than SOC, SWC, soil water matric potential (SWP), and tillage frequency.

MATERIALS AND METHODS

Site Description

We studied a long-term cropping system trial, the ‘Hunter Rotation Experiment’ initiated in 1969 at the Pennsylvania State University R.E. Larson Agricultural Research Center at Rock Springs, PA (40° 42'N, 77° 58'W, 350 m elevation). This experiment station is located in Centre County, PA 10 miles from Penn State's University Park campus. The climate of central PA is continental with 975 mm mean annual precipitation and mean monthly temperatures ranging from 3°C (Jan.) to 21.6°C (July). In 2005, the monthly precipitation at the experiment site varied from 38 mm in April to 141 mm in Oct. The soil at the experimental site is a Hagerstown series (fine, mixed, mesic, Typic Hapludalfs) which consists of well-drained limestone residual soils with high agricultural productivity (Braker, 1981). Ninety percent of the site is Hagerstown silt loam with a 0-3% slope, slow runoff and only a slight erosion hazard.

Four Cropping Systems

The experiment initially had five cropping systems which were modified in 1990 to four systems: continuous corn (C-C); corn-soybean (C-S); four years of corn-four years of alfalfa (4C-4A); and corn-oats-double-cropped with winter wheat-2 years of red clover+ timothy hay (C-O/W-2RT). During the previous 16 years, on average corn and soybean were planted in mid-May and harvested in mid-Nov. In the diverse system, the oats and wheat were double-cropped; oats were planted in the last week of April and harvested in mid-Aug., followed by winter wheat planted in mid-Oct. The wheat was harvested in the last week of July of the following year, followed by red clover+ timothy planted in mid-Sept. The fourth year alfalfa and the second year red clover were plowed under in spring before planting corn in the perennial and diverse systems. The soil was mold-board plowed in this study, and lime and inorganic N, P, and K were applied based on annual soil test recommendations of the Pennsylvania State University Agricultural Analytical Laboratory.

Soil Sampling and Analysis

We sampled soils under 10 crops from the four cropping systems and categorized them into four crop types for comparison: SA_a, SA_p, SG, and PR as described in Table 1. We collected 12 soil cores of 7.5 cm diameter to 0-15 cm depth from each of the four blocks of the 10 crops in spring (26 May), summer (13 July, 22 Aug.) and autumn (1 Nov.) of 2005. The composite samples were mixed well manually and then divided into three parts in the field for analyses. The first portion was transported and stored in airtight plastic containers at 4˚C and analyzed for WSA. The second portion was used for SWC and SWP, and the third for SMBC and SOC measurements. These latter portions were stored in plastic bags at 4˚C and analyses performed within one-two weeks of sampling.

Aggregate Stability

We measured % WSA by slightly modifying the standard wet-sieving technique (Kemper and Rosenau, 1986) based on our preliminary results and review of literature. We screened the soil to obtain 1-2 mm macroaggregates and air-dried them at room temperature for 24 hours. We used slaking instead of misting for rewetting the air-dried aggregates, because slaking mimics field conditions, is more rigorous and is more likely to detect potential differences among the crop treatments than misting (Elliott, 1986; Eviner and Chapin, 2002). We also increased the duration of wet-sieving from three to five minutes (Amezketa et al. 1996). Four grams of the air-dried 1-2 mm aggregates were transferred to the 0.26 mm size sieve of the standard sieving machine (Fig. 17-1 in Kemper and Rosenau, 1986; Five Star Cablegation and Scientific Supply, Kimberly, ID). The samples were then slaked by submerging in distilled water for 5 minutes before the sieving started. The sieves were raised and lowered for 5 minutes @ 36 cycles minute^{-1}

with a stroke length of 1.0 cm. Material that passed through the sieve after 5 minutes was collected in the metal can, oven dried, and weighed to estimate unstable aggregates. The soil that remained on the sieve was then subjected to dispersion for 30 s using an ultrasonic probe to disintegrate sand particles from the aggregates. Sand particles were retained on the sieve, and the soil that passed through the sieve was collected in another can, oven dried (110˚C) and weighed to estimate sand-corrected stable aggregate mass. The percent water stable aggregates were calculated as:

WSA = (sand-corrected stable soil/ [Unstable soil + sand-corrected stable soil]) x 100

Soil Water Content and Matric Potential

We determined gravimetric water content (%) of the unsieved soil by oven drying the samples (110˚C) to a constant weight (Gardner, 1986). We also determined SWP using a filter paper technique (Hamblin, 1981; Campbell and Gee, 1986). We placed an oven-dried and weighed Whatman filter paper (no. 42, diameter 5.5 cm) in an air-tight plastic container covering one side of the paper with about 150 grams of soil. We then placed the containers in Styrofoam boxes at room temperature for 60 hours to allow the filter papers to reach equilibrium with the soil. After 60 hours, we measured the moist weight of the cleaned filter paper to determine its moisture content. We obtained soil water matric potential from moisture content of the filter paper using the equations of Campbell and Gee (1986):

$\Psi = -\exp(7.46 - 16.7\,w)$, for $w<0.54$; and

$\Psi = -\exp(-0.23 - 2.4\,w)$, for $w>0.54$

Where 'Ψ' is matric potential in bars; and

'w' is the mass-basis water content of filter paper i.e. moisture fraction on dry wt basis

Total Soil Organic Carbon

We air-dried the soil samples, sieved to 2-mm, and further sieved the sub-samples to pass 0.25-mm for determination of SOC by diffuse-reflectance Fourier-transform infrared spectroscopy using a Bruker Optics spectrometer and an optical sampling accessory from Pike Technologies, Madison, WI. The multivariate infrared calibration for SOC was developed using partial-least squares regression (PLSR) [Janik and Skjemstad, 1995; Janik et al, 1998; Masserschmidt et al, 1999; Reeves et al, 2001] using a calibration set developed from 0-15 cm soil cores collected from the Hunter Rotation Experiment in the autumn of 2004 (multiplicative scatter correction, 9 PLSR factors, root-mean-square of cross-validation= 0.11, R^2= 0.86, SOC range 0.97 - 2.48). Total soil organic carbon values (Pella, 1990; Nelson and Sommers, 1996) for the calibration specimens were derived from loss-on-ignition (LOI) data (Sculte, 1995) using a 9-specimen SOC-LOI calibration (R^2= 0.96, standard-error of calibration= 0.06).

Soil Microbial Biomass Carbon

We determined the SMBC using the Chloroform Fumigation Extraction technique (Vance et al., 1987; Horwath and Paul, 1994). Fifteen grams of soil were incubated for 5 days with and without ethanol-free chloroform in a vacuum desiccator. A vacuum was pulled at the beginning of the incubation to facilitate even distribution of chloroform in the desiccator. The desiccator was opened after 5 days under an extraction hood and a vacuum pulled to allow for maximum evaporation of the chloroform. Carbon was extracted with a 5:1 0.5 M K_2SO_4 to soil mixture with shaking for one hour. The soil extract was filtered (Whatman filter no. 42) and organic carbon concentration in the filtrate determined using a Shimadzu Carbon Analyzer (TOC-5000A, Columbia, MD). Soil microbial biomass carbon was represented as the difference in extracted carbon between the fumigated and non-fumigated soils, or C_{flush} (Fierer and Schimel, 2002).

Experimental Design and Statistical Analysis

The experimental design was a randomized complete block with four replicates. Analysis of variance (ANOVA) was conducted on the data using the mixed procedure (PROC MIXED) [SAS Institute, 1999]. The four crop types nested in cropping systems, cropping systems, and dates were analyzed as fixed effects, the blocks as random effects, and the dates were analyzed as repeated measures.

The interaction of crop types nested in cropping systems by dates was significant ($P<0.05$; Fig. 1). Therefore, in a post-hoc analysis, we divided the data into two sets: spring to summer (May-Aug.); and summer to autumn (Aug.-Nov.). We conducted analysis of covariance (ANCOVA) on the WSA data from May-Aug. with time as a covariate using PROC MIXED (SAS Institute Inc., 1999). We compared slopes and intercepts of WSA regressed on time among the four crop types using pre-planned contrasts at $P < 0.05$. For Aug.-Nov. data, we calculated % decrease in WSA in soils for each crop type and compared with a paired t-test (SAS Institute Inc., 1999). We also compared WSA among the soils under corn in the four cropping systems because corn was the only common crop among the four systems. In the ANCOVA, the WSA in soils under the corn crops of the four cropping systems had a common slope over time. When treatments have a common slope at different levels of the covariate (e.g. dates) in ANCOVA, the treatments can be compared at any level of the covariate. Therefore, we compared the WSA data among the soils under corn in the four systems only for May, 2005 using Tukey's test at $P < 0.05$.

Regression Analysis of Estimated Live-root and Tillage Variables

We conducted regression analysis to test whether estimated period of live-root activity or soil disturbance frequency was a better predictor of WSA. Six variables were defined and calculated based on estimated live-root period and tillage frequency of the crops and cropping systems, using a common denominator of 96 months which was the longest duration of the 4C-4A cropping system (Tables 2a, b). We analyzed these variables using stepwise regression (SAS Institute Inc., 1999) with alpha=0.05 for entry and removal of the variables in the model.

Regression Analysis of Soil, Estimated Live-Root and Tillage Variables Combined

We also conducted stepwise regression (SAS Institute Inc., 1999) by combining all the estimated live-root and tillage variables, and the quantified soil variables to assess if the period of live-root activity and SMBC predicted WSA better than SOC, SWC, SWP and tillage frequency. The significance level for entry and removal of the variables in the model was alpha=0.05.

RESULTS

WSA among Soils under the Four Crop Types

In the ANOVA of WSA, the main effects of cropping systems, dates, crop types, and the interactions of date x cropping system and date x crop type (cropping system) were all significant (P<0.05). When the WSA data were divided into two periods, WSA differed significantly among the soils of 10 crops and the four crop types at all four dates (P<0.05; Fig. 1).

May-August

Water-stable aggregate percentages were significantly higher and varied less in soils of the PR, SG and SA_p than in soils of the SA_a from May through Aug. (P < 0.05; Fig. 1). Water-stable aggregates in soils of the PR were 149% higher in May, 116 in July, and 52 in Aug. than WSA in soil of the SA_a. Water-stable aggregates in the soils of SG were 130% higher in May, 118 in July, and 72 in Aug. than WSA in soil of the SA_a. Water-stable aggregates in the soils of SA_p were 106% higher in May, 89 in July, and 67 in Aug. than WSA in soil of the SA_a. However, the WSA in soils of the PR and SG were similar at all three dates.

Changes in WSA differed among soils of the four crop types from May-Aug. (P<0.05; Fig. 1). The WSA in soils of the SA_a and SA_p increased linearly from May-Aug. By contrast, the WSA in soils of the PR and SG showed a quadratic trend with an increase from May-July followed by a decrease or a no change from July-Aug.

August to November

Percent decrease in WSA from Aug.-Nov. also differed significantly among soils of the four crop types (P<0.05; Fig. 1, Table 3). The % decrease in WSA of soils under the SA_a was 1.6 fold greater than the % decrease in WSA of soil under the PR and SG. Percent decrease in the WSA of soil under the SA_p was 1.6 fold greater than the %

decrease in WSA of soil under the SG, but similar to the % decrease in WSA of soil under the PR and $SA_{a.}$

Water-stable Aggregates under Corn of the Four Cropping Systems in May

Water-stable aggregates differed significantly among the soils under corn in the four cropping systems in May (P<0.05; Fig. 2). The highest WSA were recorded in the soils of the corn in the C-O/W-2RT system and were 1.5 fold higher than WSA in soil of corn of the 4C-4A, and 2.5 fold higher than the WSA in soils of corn in the C-C and C-S systems. Percent water-stable aggregates in soil of fourth year corn in the 4C-4A system were 1.5 fold higher than the WSA in soils of corn in the C-C and C-S systems.

Regression Analysis of the Estimated Live-root and Tillage Variables

Regression analysis of tillage variables indicated that *proportion of time of cropping system with tillage* (CSPT) did not explain much variability (R^2=0.03), while *time since tillage* explained a larger but small amount of variability in WSA data (R^2= .11). The stepwise regression of WSA on the estimated live-root and tillage variables selected only the *proportion of time of cropping system with live roots* (CSPLR) as predictive of WSA, explaining about two-thirds of the variability in WSA of the soils of the four cropping systems. The regression equation was:

WSA= -12.42+ 54.8 CSPLR   (R^2= 0.67; P<0.0001)

Regression Analysis of Soil, and Estimated Live-root and Tillage Variables

The stepwise regression of WSA on the soil, and estimated live-root and tillage variables combined, selected the CSPLR, SWC and SMBC (in that order) as explaining 95% of the variability in WSA (Table 4). The regression equation was:

WSA = 8.14+ 50.8 CSPLR– 1.29 SWC+ 0.0341 SMBC (R^2= 0.95; P<0.0001)

DISCUSSION

Our hypothesis regarding the differences in WSA among soils of the four crop types was partially supported. As hypothesized, the WSA in soils of the SA_a were significantly lower than the WSA in soils of the PR and SG. Other researchers have also reported greater WSA in the soils under perennials than in the soils under annuals (Angers and Mehuys, 1988; Stone and Buttery, 1989; Drury et al., 1991; Rachman et al., 2003). However, contrary to our hypothesis, the WSA in soils of the SA_p were similar to the WSA in soils of the PR and SG. This illustrates that cropping systems had a significant effect on WSA. Due to the positive effects of the preceding PR on the soil, the WSA were maintained at high levels even during the SA_p. In the 4C-4A system, we measured WSA in soil of the fourth year corn, which still had higher WSA than soil of the SA_a.

As hypothesized, the WSA varied more in the soils under the SA_a and SA_p than in the soils under the PR and SG from spring-summer and summer-autumn. This temporal variation in aggregate stability could be due in part to differences in root biomass and activity (Baldock and Kay, 1987; Perfect et al., 1990b; Drury et al., 1991; Angers et al., 1993). For instance, summer annual crops such as corn and soybean experience a considerable variation in live root biomass and activity during the year, with roots starting to grow in spring, reaching a peak in summer and senescing after maturity in autumn. By contrast, PR and SG such as oats/winter wheat support live roots in autumn, winter and spring months in addition to the summer months.

When WSA among the soils under corn in the four cropping systems were compared in spring, WSA were higher in the soils of corn in the perennial and diverse systems than in the soils of the corn in annual systems. These results agree with earlier studies (e.g. Rachman et al., 2003), and indicate the cumulative positive effects of the perennial and diverse cropping systems on soil. In the annual systems, plant cover and live roots were present only from spring-early autumn followed by a fallow period from autumn to the following spring. Conversely, in the perennial and diverse systems, plant cover and live roots were present in the autumn, winter and early spring months also, thus supplying organic carbon and promoting biological activity for a longer period than the annual systems. Further, WSA were higher in the soil of corn in the diverse system that had a higher proportion of the years with live roots than in the soil of the year-4 corn in the perennial system. Peters et al. (1997) also reported the highest WSA in soils of a farming system in which green manure, hay or small grain crops were present in winter in addition to summer crops. These systems maintained live plant cover (and hence live roots) for a longer period than a corn-soybean system that did not include living plants during the winter months. Similarly, Villamil et al., (2006) reported up to 17% increase in WSA by including winter cover crops in a no-till corn-soybean system.

The results of the regression analysis of live roots and tillage variables also supported our hypothesis that the period of live-root activity would have a greater effect on WSA than frequency of soil disturbance. The regression analysis, however, had the limitation that the estimated values of predictor variables had a small range for predicting WSA. In addition, long periods of live roots, particularly under perennial crops, are also associated with reduced soil disturbance; therefore effects of the presence of live roots and reduced soil disturbance were probably confounded in this study. Similarly, other factors such as aboveground biomass, which could potentially influence WSA, were not included in the analysis.

The diverse cropping system had the highest CSPLR and also the highest WSA (Table 2b, Fig. 2). Although the soil of the diverse system was disturbed more frequently than the perennial system, as indicated by a greater CSPT (0.083 vs. 0.052; Table 2b), the WSA in the soil of the diverse system were higher with a concurrent higher CSPLR than the perennial system (0.813 vs. 0.750; Table 2b). Most importantly, the stepwise regression indicated that the CSPLR was the single most important variable for predicting WSA. These findings agree with earlier studies reporting plant roots as a major binding agent for stabilizing soil aggregates (e.g. Tisdall and Oades, 1980; Stone and Buttery, 1989; Miller and Jastrow, 1990; Perfect et al., 1990b; Jastrow et al., 1998). These results suggest that high WSA can be maintained even under frequent soil disturbance by designing cropping systems that have live roots present for a high proportion of time. Including crops such as double-cropped small grains, winter cover crops and perennials in rotation with summer annual crops could increase the proportion of time of a cropping system with live roots.

The stepwise regression of WSA on the soil variables, and estimated live-root and tillage variables combined, also indicated that the CSPLR was the most important variable for predicting WSA, and that the combined variables of CSPLR, SWC and SMBC exerted the most influence on WSA. Other studies have also reported a relationship between these soil variables and WSA. The effect of SWC on WSA could be due to physio-chemical factors such as cohesive forces, shear strength, osmotic effects and dissolution of stabilizing material (Kemper and Rosenau, 1984; Le Bissonnais and

Singer, 1992; Watts et al., 1996). The effect of SWC on WSA is also mediated by plant roots. Plant roots extract soil water, and thus cause soil drying which partially enhances aggregate stability by promoting the binding of root exudates on soil particles (Reid and Goss, 1982; Perfect et al., 1990a). Root exudates also reduce wetting rate, and slaking of aggregates by occluding or affecting soil porosity (Caron et al., 1996). The drying-wetting cycles induced by roots via the above mentioned processes also promote WSA (Reid and Goss, 1982, Denef et al., 2001).

Likewise, in addition to physio-chemical factors, plant roots also influence SMBC by providing food for microbial populations, promoting fungal hyphae, mycorrhizal glomalin production, bacterial mucilages, and soil binding organic polymers which reduce wetting and slaking of soil aggregates (Gupta and Germida, 1988; Jastrow et al., 1998; Chenu et al., 2000; Haynes, 2000; Wright and Anderson, 2000).

Total soil organic carbon did not explain any variability in WSA among the crops, suggesting that the labile pools of soil carbon such as plant roots, root exudates and SMBC were more important for improving WSA than SOC. These results are confirmed by other studies (e.g. Carter et al., 1994; Golchin et al., 1995). Tisdall and Oades (1982) suggested that water-stability of macroaggregates depends primarily upon temporary binding agents such as plant roots and fungal hyphae. Root derived carbon promotes WSA because of its continuous supply and high retention as occluded particulate organic matter (POM)-carbon in soil aggregates (Gale et al. 2000a, b; Puget and Drinkwater, 2001).

CONCLUSIONS

In this long-term experiment, cropping systems had a more pronounced effect on WSA than the individual crops in the systems. Percent water-stable aggregates in the soils under corn of the perennial and diverse cropping systems were significantly higher than in the soils under corn of the annual systems. Percent water-stable aggregates varied more in the soils under the SA_a and SA_p than in the soils under the PR and SG from spring through autumn. From spring-summer, WSA increased in soils under all crops; from summer-autumn, WSA decreased linearly in soils under the SA_a and $SA_{p,}$ and decreased or did not change in the soils under the PR and SG. The CSPLR predicted the WSA, while the CSPT did not. The CSPLR explained the most variability in WSA in combination with SMBC and SWC. This study provides evidence that WSA can be improved with long-term cropping systems that have live roots present in soil for a high proportion of the year.

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Table 1. Cropping systems and crops studied for comparing soil water-stable aggregates (WSA) in spring, summer and autumn of 2005 in the Hunter Rotation Experiment, Rock Springs, PA.

Cropping system type	**Cropping system**	**Crops studied**	**Crop type†**
Annual	Continuous corn	Corn (CC)	SA_a
	Corn-soybean	Corn, soybean (CS, SC)	
Perennial	4 yr corn- 4 yr alfalfa	Year 4 of corn (4C)	SA_p
		Year 4 of alfalfa (4A)	PR
Diverse	Corn-oats-wheat-2 yr redclover+ timothy	Corn (Cd)	SA_p
		Oats, wheat (O, W)	SG
		Year 1 and 2 of Red clover+ timothy (RT1, RT2)	PR

† SA_a, summer annual crops in annual systems; SA_p, summer annual crops in perennial and diverse systems; PR, perennial crops; SG, double-cropped small grain crops

Table 2a. Description of variables based on estimated live-root activity period and tillage frequency in the cropping systems and crops of the Hunter Rotation Experiment, Rock Springs, PA.

Parameter	Crop/cropping system	Variable	Estimation
Live roots	Cropping System	*Proportion of time with live roots*	Number of months with live roots/ number of months of cropping system
	Crop	*Period of live roots*	Number of months with live roots
Tillage	Cropping System	*Proportion of time with tillage*	Number of tillage events/ number of months of cropping system
	Crop	*Proportion of time with tillage*	Number of tillage events/ number of months of crop
	Crop	*Tillage frequency*	Number of tillage events/year
	Crop	*Time since tillage*	Number of months since last tillage

Table 2b. Estimates of *cropping system proportion of time with live roots* (CSPLR) and *cropping system proportion of time with tillage* (CSPT) for the four cropping systems of the Hunter Rotation Experiment, Rock Springs, PA.

Cropping system†	Number of months with live roots‡ (a)	Number of tillage events (b)	Number of total months§ (c)	CSP LR (a/c)	CSPT (b/c)
C-C	48	8	96	0.5000	0.083
C-S	48	8	96	0.5000	0.083
4C-4A	72	5	96	0.7500	0.052
C-O/W/2RT	78	8	96	0.8125	0.083

† C-C, continuous corn; C-S, corn-soybean; 4C-4A, 4 yr corn followed by 4 yr alfalfa; C- O/W-2RT, corn-oats double cropped with wheat- 2 yr red clover+ timothy.

‡ Based on planting and harvesting time of crops.

§ Total months based on the cropping system with the longest duration (8 years, 4C-4A).

Table 3. Changes in Water-Stable Aggregates (WSA) of soils under the four crop types of the Hunter Rotation Experiment, Rock Springs, PA (Aug.-Nov., 2005).

Crop type†	**Decrease in WSA (Aug.-Nov.)**	**Standard error of mean**
	%	%
SA_a	45.0 a*	3.3
SA_p	41.3 ab	3.9
PR	29.5 bc	3.3
SG	25.9 cd	3.9

* Means with different letters differ significantly using pre-planned contrasts at P=0.05.

† SA_a, summer annual crops in the annual systems; SA_p, summer annual crops in the perennial and diverse systems; PR, perennial crops; SG, double-cropped small grain crops.

Table 4. Relationship of estimated soil, live roots, and tillage variables with percent water stable aggregates

Variable	Partial R-square	Model R-square
Proportion of time of cropping system with live roots (CSPLR)	0.68	0.68
Soil water content (SWC)	0.24	0.92
Soil microbial biomass carbon (SMBC)	0.03	0.95

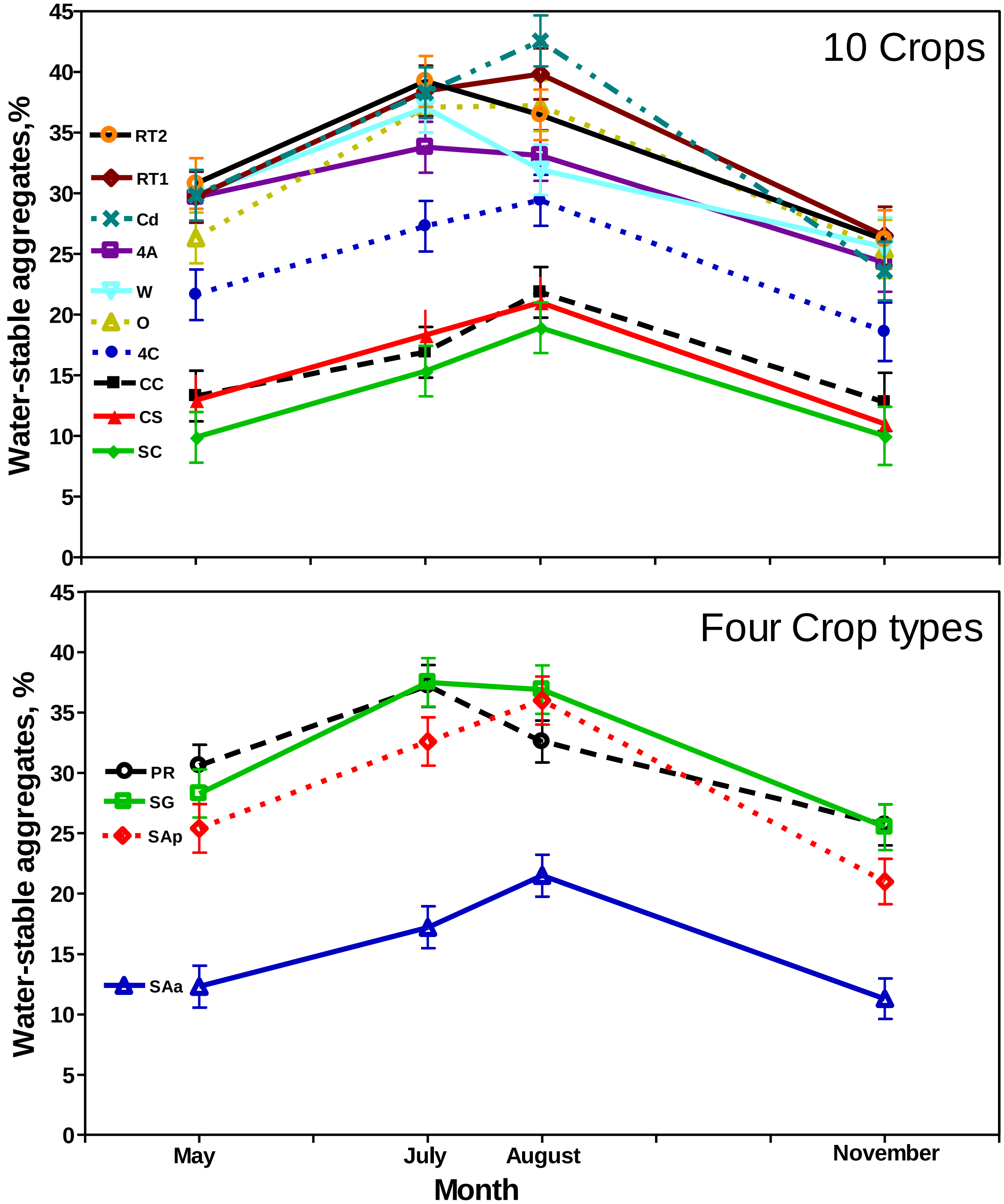

Fig.1. Water-stable aggregates in soils under the 10 crops and four crop types of the Hunter Rotation Experiment, Rock Springs, PA in May, July, Aug. and Nov., 2005. Each data point is an average of eight replicates. Crops were RT2,

yr 2 red clover; RT1, yr 1 red clover; Cd, corn in diverse system; 4A, yr 4 alfalfa; W, wheat; O, oats; 4C, yr 4 corn; CC, continuous corn; CS, corn following soybean; SC, soybean following corn. Crop types were PR, perennial crops; SG, double-cropped small grain crops; SA_{p}, summer annual crops in the perennial and diverse systems; SA_{a}, summer annual crops in the annual systems.

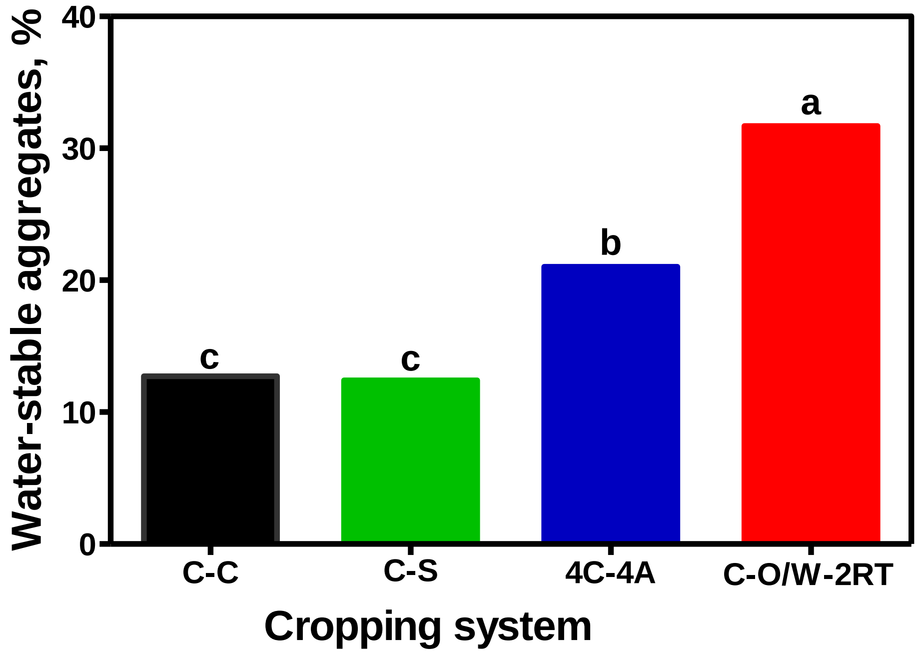

Fig. 2. Water-stable aggregates (1-2 mm) in the soils of the corn crops in four cropping systems of the Hunter Rotation Experiment, Rock Springs, PA in May, 2005. Means with the different letters differ significantly with Tukey's test at *P*=0.05 level. Cropping systems were C-C, continuous corn; C-S, corn-soybean; 4C-4A, 4 yr corn followed by 4 yr alfalfa; C-O/W-2RT, corn-oats double cropped with wheat- 2 yr red clover+ timothy.

CHAPTER 3

CORN GRAIN YIELDS AND YIELD STABILITY IN FOUR LONG-TERM CROPPING SYSTEMS

ABSTRACT

Most long-term studies evaluate only average crop yields and overlook year-to-year yield variability which could be highly significant. We hypothesized that corn (*Zea mays* L.) yields would be higher, more stable and increase more over time in i) perennial and diverse cropping systems compared to annual systems, and ii) manure-fertility compared to inorganic-fertility regimes. We studied corn yields over a 16-yr period in four cropping systems: i) continuous corn (CC); ii) corn-soybean [*Glycine max* (L) Merr.] (CS); iii) 4yr corn-4yr alfalfa [*Medicago sativa* L.] (4C4A); iv) corn-oats (*Avena sativa* L.)/winter wheat (*Triticum aestivum* L.)-2yr red clover (*Trifolium pratense* L.)+ timothy, [*Phleum pratense* L.] (COW2RT). Fertility regimes were inorganic, or manure based on crop N- or P-requirements. Mean yields in 4C4A and COW2RT were 10-12% higher than CC and 7% higher (in 4C4A) than CS. Yield trends did not differ significantly (0.28 Mg ha^{-1} yr^{-1}) among the four treatments over time. Coefficient of variation (CV) analysis indicated that yield variability across fertility regimes was highest in CC (CV = 28%) and lowest in 4C4A (CV = 21%). According to regression stability analysis, response of corn yields to the environmental conditions did not differ among four cropping systems within inorganic and P-based manure fertility. Under N-based manure fertility, however, yields diverged between CC and other systems in the poorest-yielding year but converged in the highest-yielding year. Response of corn yields to the environmental conditions did not differ between manure- and inorganic-fertility, but yields were 7% higher under manure-fertility in the poorest-yielding year. Results suggest that compared to CC, perennial and diverse systems are likely to produce higher yields across three fertility regimes, and more stable yields under N-based manure fertility.

Abbreviations

CC, continuous corn; COW2RT, corn-oats-wheat-red clover+ timothy; CS, corn-soybean; CV, coefficient of variation; 4C4A, 4yr corn-4yr alfalfa.

Year-to-year variability in crop yields is mainly influenced by environmental factors, pest pressures, and management (Varvel, 2000; Batchelor et al., 2000; Hu and Buyanovsky, 2003; Meyer-Aurich, 2006; Mallory and Porter, 2007). Understanding the temporal variability of crop yields has implications for sustainable crop production because of greater fluctuations of crop yields projected due to global climate change (Wetherald and Manabe, 1995; Dai et al., 2001; Weiss and Bradley, 2001; Pathak et al., 2003). Evaluation of crop yields, therefore, should include two indicators- yields and stability of yields across variable climatic conditions (Swift, 1994).

Long-term studies are vital for identifying cropping systems with high and stable yields and low production risk (Raun et al., 1993; Lotter et al., 2003; Girma et al., 2007; Stanger et al., 2008). Such studies can help identify crops with synergistic effects on crop productivity across variable environments over time and, therefore, can provide guidelines for management recommendations (Hildebrand, 1984; Mitchell et al., 1991; Varvel, 2000; Anderson, 2005; Mallory and Porter, 2007). Considerable research has focused on evaluating corn grain yields among cropping systems by comparing average yields, but not the stability of crop yields (Howard et al., 1998; Pederson and Lauer, 2002; Porter et al. 2003; Pikul et al., 2005).

Interpretation of year-by-cropping system interaction is difficult using the conventional ANOVA approach for long-term studies due to complexity of factors influencing environment (Raun et al., 1993). Regression stability analysis is an effective technique to visually interpret year-by-cropping system interactions (Hildebrand, 1984). This technique was used to assess genotype-by-environment interactions in plant breeding research (Yates and Cochran, 1938), and has been extended to management studies (e.g. Hildebrand 1984; Guertel et al., 1993; Blaise et al., 2006; Mallory and Porter, 2007). With this technique, "environment means" are calculated as the annual mean yields of all treatments together (Finlay and Wilkinson, 1963; Eberhart and Russell, 1966) and ranked from the poorest to the highest yields to produce a quantitative gradient of environmental conditions irrespective of the cause of variability in yields (Hildebrand, 1984). Then individual treatment means are regressed on the environment means and regression lines are compared among treatments. Coefficient of variation is another variable used to quantify and compare year-to-year variability of yield (Lin et al., 1986; Mallory and Porter, 2007; Smith et al., 2007).

Yield advantages of crop rotations compared to monocultures are well-documented (Karlen et al., 1994). For instance, corn rotated with soybean has been reported to produce 3-23% higher grain yields than corn monoculture in various short- and long-term studies (Crookston et al. 1991; Lauer et al., 1997; Howard et al., 1998; Katsvairo and Cox, 2000b; Pedersen and Lauer, 2002; Pedersen and Lauer, 2003; Wilhelm and Wortmann 2004). With diverse and perennial-based crop rotations, yield advantages over monocultures are often greater as compared to short rotations of annual crops such as corn and soybean (Meyer-Aurich et al., 2006; Stanger et al., 2008; Posner et al., 2008). The explanation for these yield advantages has been described as due to the "rotation effect" (Pierce and Rice, 1988) suggesting a combination of multiple factors such as reduced pest infestations (Liebman and Dyck, 1993; Howard et al., 1998); improved crop water use efficiency (Copeland et al., 1993; Tanaka et al., 2005); and improved soil quality (Karlen et al., 2006) including soil organic carbon (Russell et al., 2006), soil aggregation (Pikul et al., 2007), nutrient availability (Liebig et al., 2002) and soil microorganisms (Williams and Schmitthenner, 1967; Turco et al., 1990).

Improved soil quality under diverse and perennial systems has been associated with higher crop yields than summer annual row cropping systems under drought (Lotter et al., 2003) and thus may produce more stable crop yields than monocultures and short duration rotations across variable environments. Yield gains with crop rotation over monoculture are often greater in low-yielding environments than in high-yielding environments (Peterson and Varvel, 1989; Raimbault and Vyn, 1991; Porter et al., 1997; Lotter et al., 2003).

The amendment of soil with animal or green manure can also improve soil quality characteristics (Lockeretz et al., 1981; Reganold, 1988; Drinkwater et al., 1995; Drinkwater et al., 1998; Parham et al., 2003; Herencia et al., 2007; Melero et al., 2008) and thus enhance crop productivity (Peters et al., 1997; Yadvinder-Singh et al., 2004; Mallory and Porter, 2007; Shen et al., 2007). The improved soil quality with organic matter additions may also enhance the capacity of a soil to produce stable crop yields across variable environments (Smolik et al., 1995; Lotter et al., 2003; Mallory and Porter, 2007).

Relatively few studies have studied year-to-year yield variability among cropping systems typical of the Northeast. We initiated this study to understand productivity and stability of corn grain yields in four long-term cropping systems under three fertility regimes. We tested the hypotheses that corn grain yields would be higher, more stable, and increase more with time in perennial and diverse cropping systems than in annual systems. We also hypothesized that corn grain yields would be higher and more stable when fertilized with manure than with inorganic fertilizers.

MATERIALS AND METHODS

Site description

We studied corn grain yields from 1990-2005 from a long-term cropping system experiment, the 'Hunter Rotation Experiment' initiated in 1969 at the Pennsylvania State University Russell E. Larson Agricultural Research Center at Rock Springs, PA (40° 42'N, 77° 58'W, 350 m elevation). We chose the 16-yr period for our study because the crop rotations and fertility treatments were consistent during this period. The experiment station is located about 16 km from Penn State's University Park campus in Centre County, PA. The climate of central PA is continental with mean monthly temperatures ranging from 3°C (Jan.) to 21.6°C (July). The soil is a Hagerstown series (fine, mixed, mesic, Typic Hapludalfs) which consists of well-drained limestone residual soils with high agricultural productivity (Braker, 1981). Ninety percent of the experimental site is Hagerstown silt loam with a 0-3% slope, slow runoff and only a slight erosion hazard. The amount of precipitation received at the site during the period of April-October varied considerably varied among the years of the study (1990-2005) from 481 mm (1991) to 1113 mm (1996) with an average of 698 mm.

The experiment was a randomized, complete-block, split-plot design with three fertility regimes as main plots, four cropping systems as subplots, and four replicates. All rotation entry points were present each year for a total of 192 plots (5.76 m by 12.80 m) that were under conventional tillage (mold-board plow followed by disking and cultimulching) for all annual and forage crop establishment.

The three fertility regimes were designed to meet crop nutrient requirements using either: (i) inorganic N-P-K fertilizers; (ii) liquid dairy manure based on the N requirement of non-legume crops (since 1990; formerly managed as inorganic fertilizer); or (iii) liquid dairy manure based on P removal requirements of each crop (since 1982; formerly managed as inorganic fertilizer). All treatments were limed to maintain a soil pH of 7 to plow depth. Fertilizer rates were determined based on annual soil tests. Inorganic fertilizers were surface broadcast by hand and liquid dairy manure was sprayed in the spring before primary tillage.

The four cropping systems included two annual systems of CC and CS; a perennial system of 4C4A; and a diverse system of COW2RT. Cropping systems CC and CS have been in place since 1969, while systems 4C4A and COW2RT were established in 1990 by combining previous sequences. During 1990-2005, on average corn and soybean were planted in mid-May and harvested in mid-Nov. In the diverse system, the oats and wheat were double-cropped; oats were planted in the last week of April and harvested in mid-Aug., followed by winter wheat planted in mid-Oct. The wheat was harvested in the last week of July of the following year, followed by red clover+ timothy planted in mid-Sept. In the perennial and diverse systems, the fourth year alfalfa and the second year red clover were plowed under in spring before planting corn.

Statistical analysis

Analysis of variance was conducted on the yield of first-year corn of the four cropping systems using PROC MIXED of SAS (SAS Institute, 1999). The cropping systems, fertility regimes and their interaction were analyzed as fixed effects; and blocks, years, and the interactions of block x fertility, block x fertility x cropping system, year x fertility, year x cropping system, and year x fertility x cropping system were random effects. Mean corn grain yields were compared among the four cropping systems using Tukey's test. Differences were considered significant at $P < 0.05$. We used a pre-planned contrast to compare mean corn yields between annual (CC, CS) and perennial and diverse (4C4A, COW2RT) cropping systems.

Yield Stability Analysis

The assumption for stability analysis is that the year-to-year variability in yields is due mainly to environmental variability. For a valid stability analysis, therefore, change in yields over time should not differ among the treatments being compared (Guertel et al., 1994). We, therefore, first examined whether the trends of corn yields over time differ among the treatments by comparing linear trends of corn yields among cropping systems within each fertility regime. We tested the equal slope hypothesis at $P < 0.05$ using PROC MIXED of SAS (SAS Institute, 1999).

To assess yield stability, annual means of cropping system treatments were regressed over the environment means (the annual mean corn grain yield of all the treatments) within each fertility regime using analysis of covariance in the mixed procedure of SAS (SAS Institute, 1999). The equal slope hypothesis ($P < 0.05$) was tested; subsequently when the equal slope hypothesis was rejected, linear slopes of the four cropping systems on the environments were compared using pre-planned contrasts ($P < 0.05$). We also compared corn yields in the lowest-yielding years for comparing intercepts among the four cropping systems within each fertility regime using Tukey's test at $P < 0.05$.

Similarly, we also analyzed time trends and stability of corn yields among the three fertility treatments averaged across the four cropping systems. We tested the equal slope hypotheses ($P < 0.05$) followed by pre-planned contrast ($P < 0.05$) of the inorganic fertility treatment, and the average of the N- and P-based manure fertility treatments using PROC MIXED of SAS (SAS Institute, 1999).

Variability of yields

We also compared the variability of corn grain yields by calculating the coefficient of variation (CV) of corn yields over time for the 12 cropping system by fertility treatments. Analysis of variance was then conducted on CV using the MIXED procedure of SAS (SAS Institute, 1999). Fertility, cropping systems and interaction of fertility x cropping systems were the fixed effects; block and interaction of block x fertility were the random effects. Mean CV's of corn grain yields among the four cropping systems were compared using Tukey's test at ($P < 0.05$).

To examine if precipitation explained variability in crop yields, we regressed seasonal total and monthly growing season precipitation over the years of study, using the stepwise regression ($P < 0.05$ for entry and removal of variables) procedure of SAS (SAS Institute, 1999).

RESULTS

Corn grain yields

Corn yields among the cropping systems and fertility treatments varied from year-to-year as indicated by the significant interactions of year x cropping system, year x fertility, and year x fertility x cropping system (Table 1). Due to the significant interaction of year x fertility x cropping system, we conducted stability analysis to compare the cropping systems within each fertility regime. Corn yields differed among the four cropping systems and years, but did not differ among the three fertility treatments.

Mean first-year corn grain yields in the 4C4A system were 12% and 7% higher than in the CC and CS systems, respectively (Fig. 1). Mean corn yields in the COW2RT system were 10% higher than the CC system. Mean corn yields in the CS system were not significantly different from the mean yields in the CC and COW2RT systems.

Variability of corn yields in four cropping systems

The CV of corn grain yields differed among the four cropping systems, but did not differ among the three fertility regimes (Table 3). When averaged across the three fertility treatments, CV of corn yields in CC was 31% higher than 4C4A and 14% higher than COWRT. Mean CV of corn yields in CS was 17% higher than 4C4A.

Time trends and stability of corn yields in four cropping systems

There was observed a positive linear trend over time in corn grain yields with an increase of 0.28 Mg ha^{-1} $year^{-1}$ which did not differ among the four cropping systems (Fig. 2).

In the regression stability analysis under the inorganic and P-based manure fertility regimes, linear slopes of treatment mean corn yields on the environment means did not differ significantly among the four cropping systems (Fig. 3a and 3c). The corn yields in the poorest-yielding year, however, differed among the four cropping systems under both the inorganic and P-based fertility regimes. Under the inorganic fertility regime, the first-yr corn yields in the 4C4A system were 41 and 24% higher than the CC and CS systems, respectively, and corn yields in the COWRT system were 28% higher than CC in the poorest-yielding year (Fig. 4a). Similarly, under the P-based manure fertility, the first-yr corn yields in the 4C4A system were 34 and 23% higher than the CC and CS systems, respectively; corn yields in the COWRT system were 19% higher than CC in the poorest-yielding year (Fig. 4c).

Under the N-based manure fertility treatment, corn yields in the CC system were less stable than the CS, 4C4A, and COW2RT systems, as indicated by greater slope of corn yields in the CC than the other three systems over the environment means (Fig. 3b). Corn yields diverged most between CC and the other three systems in the poorest-yielding year and converged as the environment mean increased (Fig. 3b). In the poorest-yielding year, first-yr corn yields in the 4C4A, COWRT, and CS systems were 33%, 25 and 20 higher than the CC system, respectively (Fig. 4b). In the highest yielding year, however, corn yields did not differ among the four cropping systems.

Time trends and stability of yields between fertility regimes

Corn yields increased linearly over years at a rate of 0.28 Mg ha^{-1} $year^{-1}$ under both the inorganic and manure (average of N- and P-based) fertility treatments. The slopes of treatment yields on environment mean did not differ between the manure-amended and inorganic fertility regimes. In the poorest-yielding year, however, corn yields were 7% higher in the manure-amended fertility regime than in the inorganic-fertility regime.

Precipitation

Over the course of the study, total rainfall in the growing season (April-August) ranged from 50 to 111 cm (Table 5). Total precipitation during the growing season was below the 13-yr mean in 9 of the 13 yr of this study. Within a growing season, CV in monthly precipitation totals ranged from 0.35 to 0.76 during the study period (Table 5). In the stepwise regression, precipitation explained 64% of the yield variability. The most significant predictors of the corn yield variability were the amounts of precipitation received during the months of July (positively related; $R^2 = 0.43$), May (negatively related; $R^2 = 0.16$), and June (positively related; $R^2 = 0.05$), in that order. The regression equation was:

Yield = 7.953 + 0.759 July rainfall – 0.0668 May rainfall + 0.418 June rainfall (R^2= 0.64; $P < 0.0001$).

DISCUSSION

The observation that mean corn yields in the perennial (4C4A) system were higher than annual systems (CC and CS) and that mean corn yields in the diverse (COW2RT) systems were higher than the CC system supports our hypothesis that corn yields would be higher in perennial and diverse cropping systems than the annual systems. The corn yield advantage of the CS rotation compared to the monoculture was not significant, but numerically, was consistent with a small positive trend (5%) as reported in the literature (Crookston et al., 1991; Peterson and Varvel, 1989a, b; Chen et al., 2001). These yields were observed on high-yielding soils for Pennsylvania. The corn yields in the CS system were also not significantly different from corn yields in the COW2RT system. Mean yields were highest for the first yr corn following 4 yr alfalfa, intermediate in the corn following 2 yr red clover and soybean, and lowest in the continuous corn. These results are in agreement with earlier studies that reported higher corn grain yields in diverse and perennial rotations than in corn monoculture (Varvel, 2000; Posner et al., 2008; Stanger et al., 2008).

Several factors may have contributed to the beneficial "crop rotation effect" such as reduced pressure of insects (Roth et al., 2006), weeds (Smith and Gross, 2006), and diseases (Larkin and Honeycutt, 2006); improved N-mineralization and availability (Russel et al., 2006) along with reduced losses of N with legumes compared to inorganic fertilizers (Drinkwater et al., 1998). Perennial and diverse cropping systems including legume crops have been reported to increase corn yields relative to monoculture even in the presence of N, P, or K fertilizers. Stanger et al. (2008) reported a 54% increase in first-year corn yield following alfalfa over corn yield in monoculture across four N rates (0, 56, 112, and 224 kg ha^{-1}) in a 15-yr study in Wisconsin.

Inclusion of perennial and diverse crops in rotations may also play an important role in improving soil quality (Russell et al., 2006). In concurrent research conducted on the same study, the soils under the perennial and diverse systems had higher water-stable aggregates, microbial biomass carbon, and total organic carbon and lower bulk density compared to the soil under corn monoculture (Grover and Karsten, in preparation). Similarly, the perennial and diverse cropping systems also enhanced soil microbial biomass carbon, and particulate and chemically labile organic matter fractions, compared to the continuous corn under the manure fertility regimes (Bucher, 2002; Bucher and Lanyon, 2004; Mirsky et al., 2008).

The improved soil quality benefits in the perennial and diverse cropping systems could be linked to relatively longer presence of live roots and thus relatively continuous supply of soil carbon and enhanced soil biological activity during the growing season (Gale et al. 2000a, b; Puget and Drinkwater, 2001; Grover and Karsten, in preparation). Reduced cultivation frequency in the perennial system could also enhance soil quality and thus yields over corn monoculture (Elliott, 1986; Smith et al., 2007).

This study also demonstrated that cropping systems can influence the temporal variability and stability of crop yields. In the CV analysis, the perennial and diverse systems produced the least variable corn yields, whereas corn monoculture had the most variable yields across three fertility regimes (Table 3). Varvel (2000) also reported that two- and four-yr crop rotation systems were more effective at reducing long-term corn yield variability than corn monoculture, in a 16-yr study in Nebraska.

In the present study, the regression stability analysis revealed that the response of cropping systems to environmental conditions differed with the fertility regimes. Under the inorganic and P-based manure fertility, the response of corn yields did not differ significantly among the four cropping systems (Fig. 3a and 3c). In the N-based manure fertility treatment, however, corn yields in the CC were less stable than in the other three cropping systems, as indicated by their greater response to environmental conditions (Fig. 3b).

The yield advantages with perennial and diverse cropping systems over annual systems were observed in the poorest- and highest-yielding years under the inorganic and P-based manure fertility treatment. Under the N-based manure fertility, however, the yield advantage of crop rotations over corn monoculture was greatest in the poorest-yielding year but diminished in the highest-yielding year, indicating that corn yields in monoculture were not significantly different than the other three systems in the high-yielding conditions with N-based manure applications. This difference in performance of CC relative to other systems between N- and P-based manure fertility treatments could be due to the differences in amounts of manure applied to the non-legume and legume crops in the cropping systems. In the N-based manure fertility treatment, manure was applied to only non-legume crops, whereas in the P-based manure fertility treatment, manure was applied to legume and non-legume crops. For instance, within the N-based manure fertility treatment, CC received 110% more manure than the first year corn after alfalfa. On average over the eight year rotation, CC received 82% more manure than the 4C4A cropping system (Table 4). By contrast, within the P-based manure fertility treatment, CC received 73% more manure than the first yr corn after alfalfa, and on average over the eight yr rotation CC received 22% less manure than the 4C4A cropping system. Relatively greater amounts of manure received by CC than 4C4A system within the N-based manure fertility treatment might have contributed towards the improved performance of CC in high yielding conditions. By contrast, within the P-based manure fertility treatment, CC did not have the advantage of receiving greater amounts of manure than the 4C4A system and, therefore, yielded lower even during high yielding conditions.

Other researchers have also reported crop rotation advantages in stressful conditions as compared to high-yielding environments. For instance, Wilhelm and Wortmann (2004) found the greatest yield advantages with corn-soybean rotation over corn monoculture during the low-yielding years with cool springs under rainfed conditions in a 16-yr study in southwestern Nebraska. Similarly, Porter et al. (1997) reported that corn yield advantages of corn-soybean rotation over continuous corn were highest in low-yielding environments in three long-term studies in the northern Corn Belt. The yield advantage of rotation over corn monoculture ranged from 25% in low-yielding environmental conditions to 15% in high-yielding environmental conditions.

Temporal variability in yields has been suggested to be mainly caused by environmental factors such as precipitation and temperature (Hu and Buyanovsky, 2003; Mallory and Porter, 2007; Tannura et al., 2008). In this study also, variability in corn yields was significantly influenced by precipitation during the growing season (Table 4). The amount of precipitation received during the months of May, June, and July together explained 64% of the yield variability. Greater than normal precipitation in May and limited precipitation in June and July had an adverse effect on corn yields. Wilhelm and Wortmann (2004) also found that corn yields increased with less than normal spring rainfall, and more than normal summer rainfall. Similarly, based on a 104-yr dataset on corn yield and climate in central Missouri, Hu and Buyanovsky (2003) found that high-yielding years had less rainfall and warmer temperatures during the planting period, more rainfall and warmer temperatures during the germination and emergence, and more rainfall and cooler-than-average temperatures in the anthesis and kernel-filling periods from June through August.

Significant positive corn yield trends were observed in all cropping systems and fertility treatments (0.28 Mg ha^{-1} yr^{-1}). These trends are higher than those reported at the National (0.15 Mg ha^{-1} yr^{-1}), State and County (0.05 Mg ha^{-1} yr^{-1}) level (USDA-NASS, 2008). It is difficult to determine the exact cause of the increasing trends. Possible explanations, however, include role of biotechnological advancements in seed-genetics, improved management practices and favorable weather. Tannura et al. (2008) advised caution against the popular perception of technology as the major driver of faster rate of yield increasing trends observed since 1990's. Based on an analysis of the long-term corn yields and weather data in Illinois, Indiana, and Iowa, they suggested that generally more benign weather since 1990's could have caused faster yield increases in the last decade. Nielson (2006) also suggested that weather influences yield trend variations more than genetics or production technologies. Further, long-term data is essential to accurately evaluate yield trends (Jones and Singh, 2000). Nielson (2006) observed that the increases in yield trends were smaller based on a long-term dataset (70 and 46 yr) than those based on a relatively short-term data (10 yr) of corn yields in Indiana.

Our hypothesis regarding yield stability between the inorganic and manure fertility regimes was partially supported. The response of corn yields to the environment mean yields did not differ between the two fertility regimes. The corn yields in the poorest-yielding year, however, were higher in the manure-fertility treatments than in the inorganic fertility treatment. Lotter et al. (2003) also reported higher corn yields in long-term manure and legume based organic farming systems compared to an inorganic system in a year of prolonged crop season drought in Pennsylvania. The authors attributed the higher crop yields with the manure- and legume-amended cropping systems to the higher water holding capacity of soils in the organic treatments. Other suggested mechanisms for the improved performance with organic amendments in stressful environments such as drought are improved soil organic carbon, (Clark et al., 1998; Drinkwater et al., 1995; Mallory and Porter, 2007; Mirsky et al., 2008); proliferation of beneficial mycorrhizal associations in crop root zones (Sylvia and Williams, 1992; Mader et al., 2000); improved soil structure (Bucher, 2002; Mallory and Porter, 2007); and enhanced crop resistance to pest pressures (Gallandt et al., 1998; Alyokhin et al., 2005). The yield advantages particularly with the manure fertility systems over inorganic fertility under adverse climatic conditions in the current study could be due to the enhanced quality characteristics such as total soil C, particulate and chemically labile organic matter C fractions, microbial biomass C, and soil aggregate stability under the manure fertility systems as reported in the previous research conducted in the same long-term study (Bucher, 2002; Mirsky, 2008).

CONCLUSIONS

The long-term perennial (4C4A) and diverse (COW2RT) cropping systems produced 10-12% higher and less variable corn grain yields than corn monoculture. Corn yield variability was associated with climatic adversity, particularly excess rainfall in spring, and low rainfall in summer. Corn yields increases over the course of the study did not differ among the annual (CC and CS) and the perennial and diverse cropping systems across the three fertility regimes (0.28 Mg ha^{-1} yr^{-1}). According to the CV analysis, yields were most variable in the CC and least variable in the first-year corn of 4C4A system across the three fertility regimes. According to the regression stability analysis, corn yield stability did not significantly differ among the four cropping systems under the inorganic and P-based manure fertility. Under the N-based manure fertility, however, corn yields in the CC were lower than the other cropping systems in the poorest-yielding years but did not differ among the four cropping systems in the high-yielding years under the N-based manure fertility. Corn yields under the manure-based fertility regimes were higher than under the inorganic fertility regime in the low-yielding years. In summary, this study indicates that compared to CC, perennial and diverse systems are likely to produce higher yields across three fertility regimes, and more stable yields under N-based manure fertility.

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Table 1. Mixed-procedure ANOVA of corn grain yields from 1990-2005 in the Hunter Rotation Experiment, Rock Springs, PA.

Source of variation	df	Mean square
Block	3	1722425 ns†
Fertility	2	4709611 ns
Block x fertility	6	2608971*
Cropping system	3	44443695**
Fertility x cropping system	6	1089193 ns
Block x fertility x cropping system	27	789780 ns
Year	14	234887706***
Year x fertility	28	1661605*
Year x cropping system	37	5042530***
Year x Fertility x cropping system	69	884759**
Residual	444	555049

***, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.**

† **ns, not significant**

Table 2. Regression slopes of corn yields on environmental means

	Inorganic fertility		**N-based manure fertility**		**P-based manure fertility**	
Cropping system†	Slope	Standard error	Slope	Standard error	Slope	Standard error
CC	1.09‡	0.05	1.12*a	0.06	1.03‡	0.06
CS	1.02	0.05	0.91b	0.06	1.09	0.09
4C4A	0.92	0.05	0.90b	0.06	0.94	0.06
COW2RT	1.04	0.05	0.94b	0.06	1.06	0.06

† Cropping systems were CC, continuous corn; CS, corn-soybean; 4C4A, 4 yr corn-4 yr alfalfa; COW2RT, corn-oats-wheat-2 yr red clover+ timothy

‡ Slopes did not differ significantly at $P < 0.05$

*** Different letters indicate significant differences at $P < 0.05$**

Table 3. Means and ANOVA of year-to-year variation, expressed as the CV, in corn grain yields from 1990-2005 in the Hunter Rotation Experiment, Rock Springs, PA.

Cropping system		Mean CV
CC		0.28a†
CS		0.25ab
4C4A		0.21c
COW2RT		0.24b
	ANOVA	
Source of variation	**df**	**Significance**
Fertility	2	ns‡
Cropping system	3	***
Fertility x cropping system	6	ns

† Means followed by the same letter are not significantly different at *P* = 0.05.

‡ ns, not significant.

***, **Significant at the 0.001 probability level.**

Table 4. Amount of manure applied to continuous corn and corn-alfalfa cropping systems in N- and P-based manure fertility treatments

Cropping system	N-based manure fertility			P-based manure fertility		
	Amount of manure applied (ton/acre)					
	1st yr corn	1st yr alfalfa	8 yr average of rotation	1st yr corn	1st yr alfalfa	8 yr average of rotation
CC	25.5	-	25.5	21.6	-	21.6
4C4A	12.3	0.0	14.0	12.3	27.0	27.5
Difference in manure applied (CC - 4C4A)	+13.3	-	+11.5	+9.3	-27.0	-5.9

Table 5. Total monthly precipitation and precipitation variability during the growing season from 1990-2005 at the Hunter Rotation Experiment, Rock Springs, PA.

	Precipitation					
Year	April	May	June	July	August	April-August
	mm					
1990	84	165	69	132	104	554
1993	230	45	84	54	56	470
1994	77	86	58	109	221	552
1995	54	94	123	30	20	321
1996	84	103	141	151	145	623
1997	35	111	72	63	182	463
1998	194	74	132	117	84	600
2000	101	82	117	71	99	470
2001	72	36	146	84	81	419
2002	84	177	139	29	55	485
2003	64	120	145	140	185	653
2004	122	94	96	247	119	678
2005	38	41	38	125	95	336
CV†	0.6	0.45	0.35	0.57	0.52	0.27

† CV, coefficient of variation of total monthly precipitation occurring in the same month over the period of study.

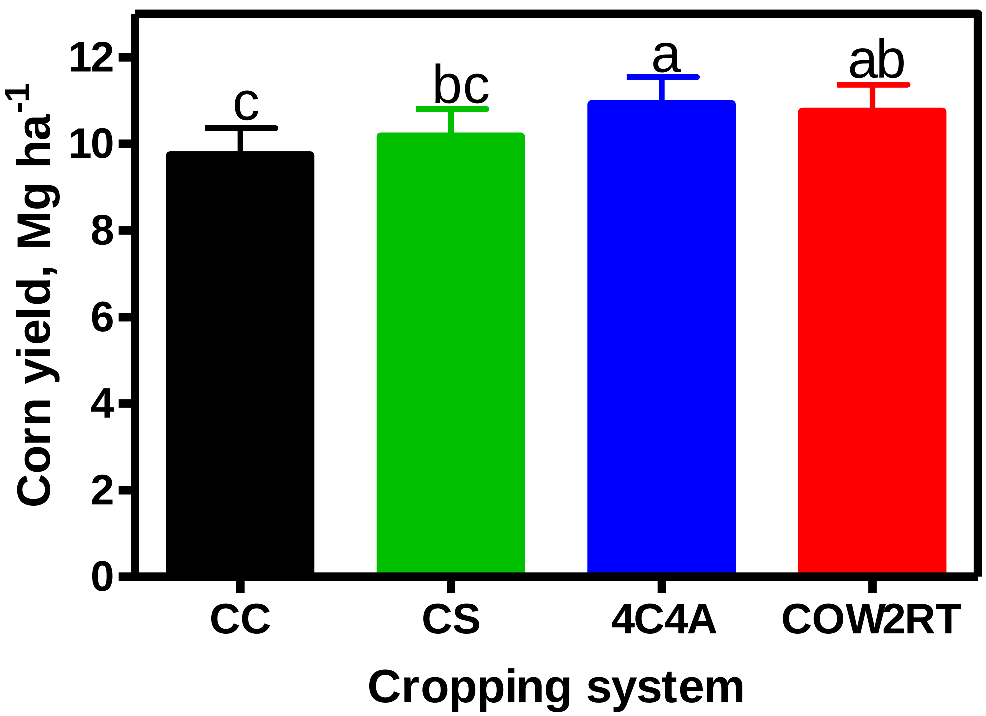


Fig. 1. Mean grain yields and standard errors of first-year corn in the four cropping systems of the Hunter Rotation Experiment, Rock Springs, PA from 1990-2005. Cropping systems were CC, continuous corn; CS, corn-soybean; 4C4A, 4 yr corn-4 yr alfalfa; COW2RT, corn-oats-wheat-2 yr red clover+ timothy. Bars with different letters indicate significant differences (*P* < 0.05) according to Tukey's test.

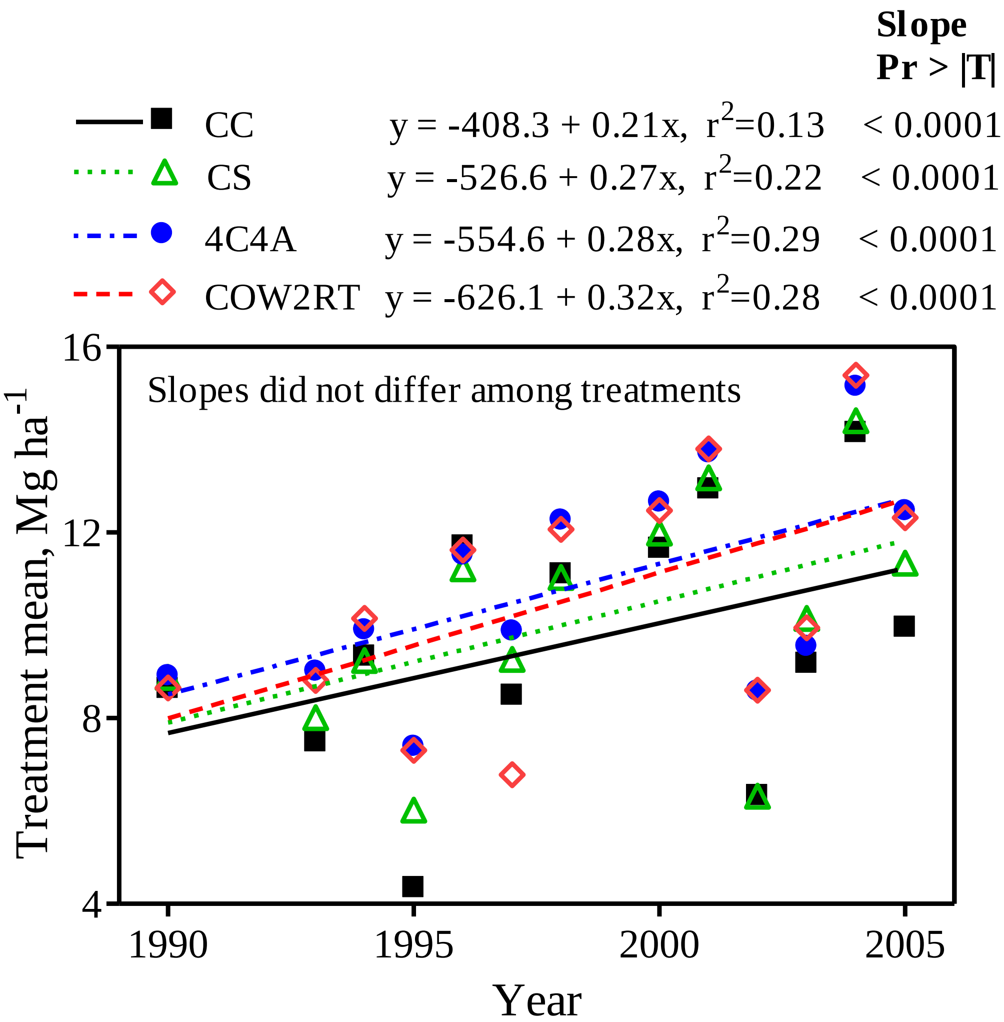
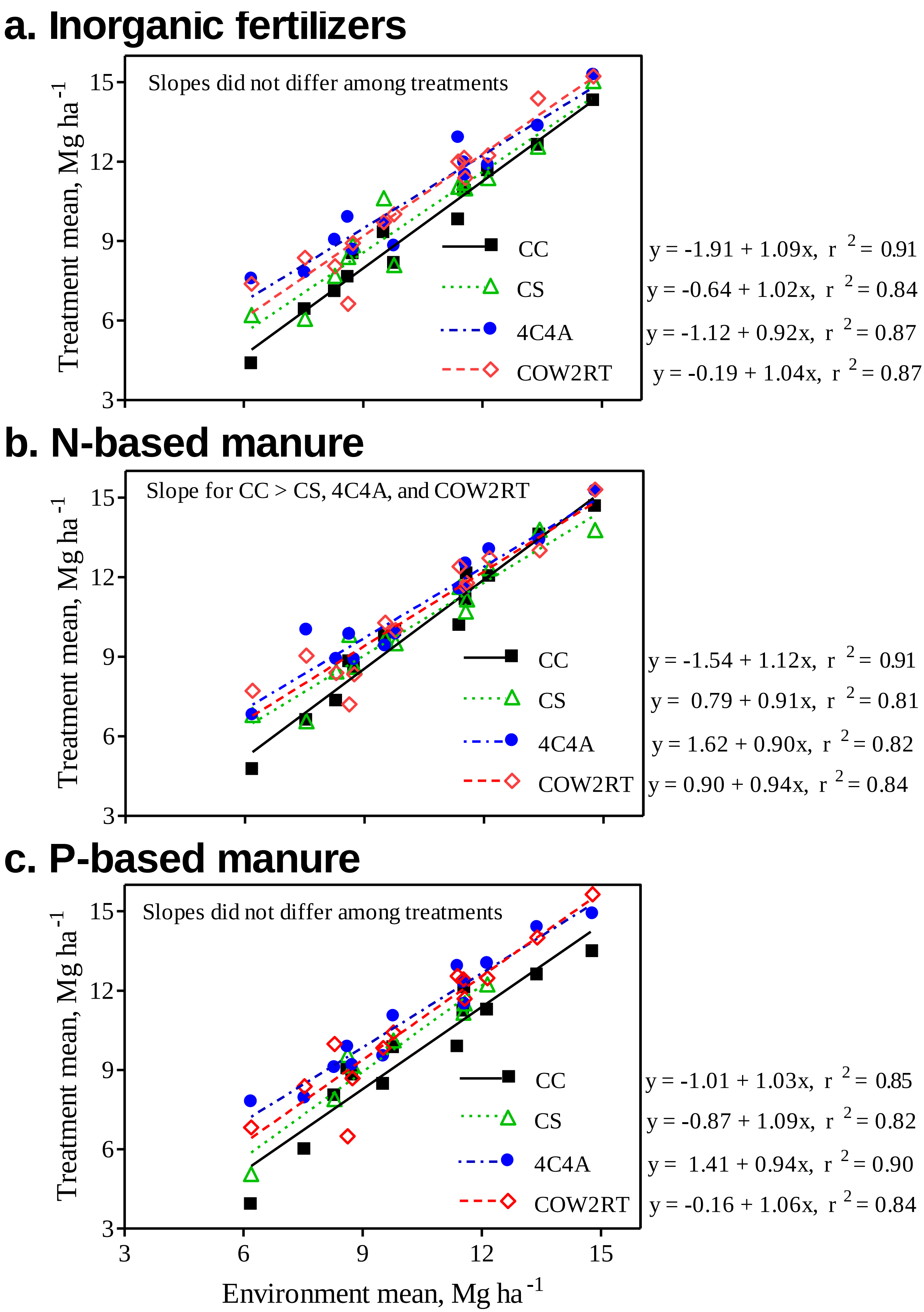


Fig. 2. Linear regressions of cropping system treatment means on years from 1990-2005 in the Hunter Rotation Experiment at Rock Springs, PA. Cropping systems were CC, continuous corn; CS, corn-soybean; 4C4A, 4 yr corn-4 yr alfalfa; COW2RT, corn-oats-wheat-2 yr red clover+ timothy. Individual data points are the mean of four replicates of three fertility regimes (n = 12). Pr > |T|, probability that slope is equal to zero. Slopes were compared among treatments with pre-planned contrasts. Differences were considered significant at *P* < 0.05.



a. Inorganic fertilizers
Slopes did not differ among treatments
CC
CS
4C4A
COW2RT
y = -1.91 + 1.09x, r 2 = 0.91
y = -0.64 + 1.02x, r 2 = 0.84
y = -1.12 + 0.92x, r 2 = 0.87
y = -0.19 + 1.04x, r 2 = 0.87
b. N-based manure
Slope for CC > CS, 4C4A, and COW2RT
CC
CS
4C4A
COW2RT
y = -1.54 + 1.12x, r 2 = 0.91
y = 0.79 + 0.91x, r 2 = 0.81
y = 1.62 + 0.90x, r 2 = 0.82
y = 0.90 + 0.94x, r 2 = 0.84
c. P-based manure
Slopes did not differ among treatments
CC
CS
4C4A
COW2RT
y = -1.01 + 1.03x, r 2 = 0.85
y = -0.87 + 1.09x, r 2 = 0.82
y = 1.41 + 0.94x, r 2 = 0.90
y = -0.16 + 1.06x, r 2 = 0.84
Treatment mean, Mg ha -1
Environment mean, Mg ha -1
3
6
9
12
15

Fig. 3. Linear regressions of cropping system treatment means on the environment means from 1990-2005 under the a) inorganic fertility, b) N-based manure fertility, and c) P-based manure fertility regimes of the Hunter Rotation Experiment, Rock Springs, PA. Cropping systems were CC, continuous corn; CS, corn-soybean; 4C4A, 4 yr corn-4 yr alfalfa; COW2RT, corn-oats-wheat-2 yr red clover+ timothy. Individual data points are the mean of four replicates (n = 4). Slopes were compared among treatments with pre-planned contrasts, and differences were considered significant at *P* < 0.05.

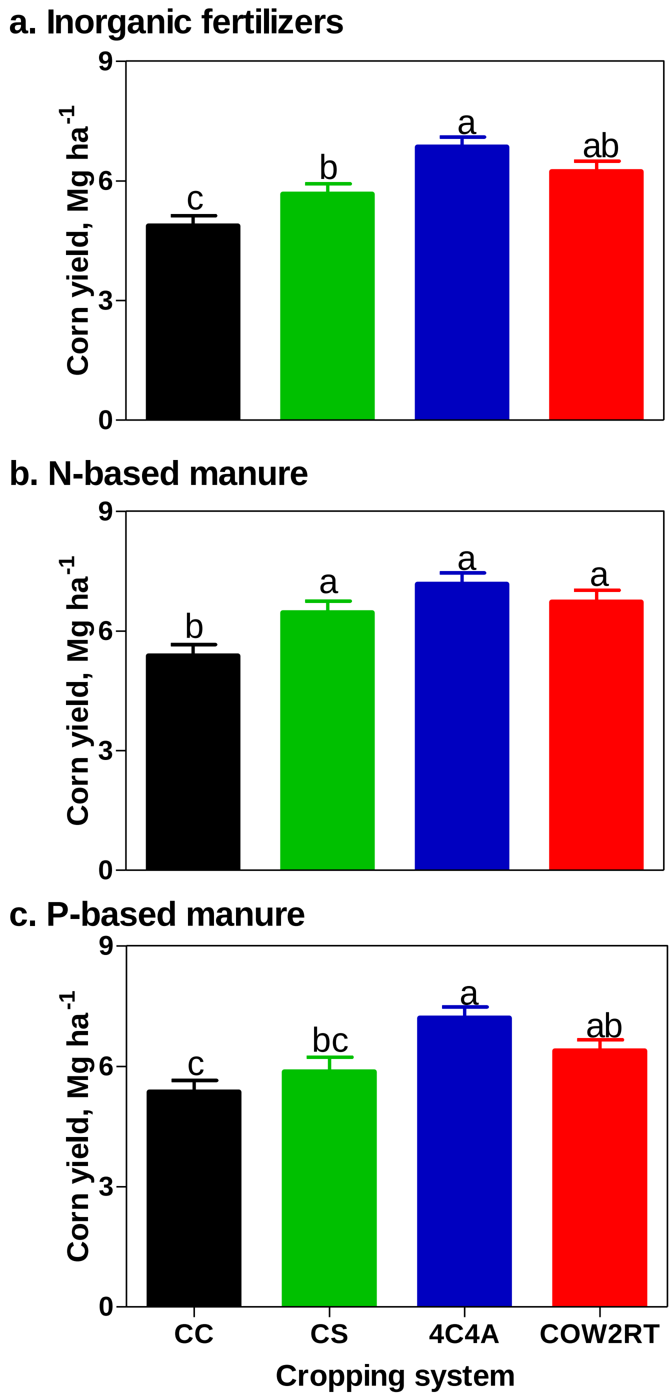

a. Inorganic fertilizers
b. N-based manure
c. P-based manure
Corn yield, Mg ha-1
0
3
6
9
c
b
a
ab
b
a
a
a
c
bc
a
ab
CC
CS
4C4A
COW2RT
Cropping system

Fig. 4. Corn grain yields in the four cropping systems in the poorest-yielding year under the a) inorganic fertilizers, b) N-based manure, and c) P-based manure fertility regimes of the Hunter Rotation Experiment, Rock Springs, PA. Cropping systems were CC, continuous corn; CS, corn-soybean; 4C4A, 4 yr corn-4 yr alfalfa; COW2RT, corn-oats-wheat-2 yr red clover+ timothy. Different letters indicate significant differences with pre-planned contrasts at $P < 0.05$.

CHAPTER 4

OVERALL CONCLUSIONS

Long-term studies provide valuable resources for generating information on the impacts of management practices on soil quality, crop yields, yield trends, and yield stability that are instrumental for designing sustainable cropping systems. In the HRE, perennial and diverse cropping systems promoted greater soil aggregate stability than the annual cropping systems. Among the crop types, perennials and double-cropped small grains promoted greater soil aggregate stability than summer annuals grown in the annual systems. The summer annuals grown in the perennial and diverse cropping systems also had greater soil aggregate stability than summer annuals grown in the annual cropping systems, indicating a more pronounced cropping system effect than individual crop-effect.

Evidence is provided that the improved soil aggregate stability with perennial and diverse cropping systems was due to the greater proportion of time that these cropping systems had live roots than the annual systems. The importance of presence of live roots for maintaining high aggregate stability was also supported by the observation that soil aggregate stability fluctuated more during the growing season under summer annuals than under perennial and double-cropped small grains, and the greater change corresponded to the greater seasonal changes in the presence of live roots of summer annuals than that of perennials and double-cropped small grains. Finally, the combined analysis of the measured soil characteristics and estimated live root and tillage variables indicated that the period of cropping system with live roots was the most important variable along with soil microbial biomass carbon and water content for predicting aggregate stability.

In summary, these results indicate that over time soil aggregate stability can be improved by designing cropping systems that include crops that occupy the soil with live roots for a high proportion of the growing season such as perennials, double-cropped small grains, and winter cover crops.

Higher corn grain yields and yield stability were also obtained with the perennial and diverse cropping systems as compared to the annual systems. On average, the first-year corn after alfalfa produced the highest corn grain yields, followed by the corn after red clover and timothy, and the corn after soybean, while the continuous corn produced the lowest yields.

According to coefficient of variation analysis, the perennial and diverse cropping systems had lower year-to-year variability in corn grain yields as compared to the continuous corn across the three fertility regimes. According to the regression stability analysis, under inorganic fertilizers and P-based manure, grain yields of the 4 systems were not significantly different. Under the N-based manure fertility, however, corn yields in the CC were lower than the other cropping systems in the poorest-yielding years but did not differ among the four cropping systems in the high-yielding years under the N-based manure fertility. Corn yields under the manure-based fertility regimes were higher than under the inorganic fertility regime in the low-yielding years.

This study indicates that compared to CC, perennial and diverse systems are likely to produce higher yields across three fertility regimes, and more stable yields under N-based manure fertility.

CHAPTER 5

PERENNIAL AND DIVERSE CROP ROTATIONS IMPROVE SOIL QUALITY AND CORN GRAIN YIELDS

Note: This chapter is intended for an outreach extension publication

Crop rotations are an important management practice for successful crop production enterprises. Crop rotations based on perennial and diverse crops have been reported to improve soil quality compared to crop rotations of only annual row crops. In Pennsylvania, crop rotations often include perennial forages, small grains, and annual row crops. Historically, corn-oats-wheat-hay was a popular crop rotation in the state. Currently, corn-alfalfa is a popular crop rotation among dairy farmers. Other common rotation grown by grain producers is corn-soybean. Many farmers apply manure to meet crop nutrient demands which also adds organic matter to the soil and benefits soil quality.

Perennial and diverse crop rotations often result in higher crop yields due to the improved soil quality benefits and reduced weed, insect and disease pressures over monoculture. Most yield comparisons are based on averages, however, and information is lacking on how crop rotations influence year-to-year yield variability. Some crop rotations are more sensitive than others to climatic stresses such as droughts and, therefore, produce more variable yields over years. Manure applications to supply crop nutrients also add organic matter to soil and, therefore, may enhance the capacity of a soil to support crop growth under stress conditions as compared to inorganic fertilizers. Long-term evaluations provide the best resources for monitoring the effects of cropping systems on soil quality and crop yields.

This publication documents the evaluation of soil quality and corn yields from a 36-year old crop rotation and fertility experiment established at the Pennsylvania State University Research Center, Rock Springs, PA. There were three fertility treatments and four crop rotations in this study as detailed in Tables 1 and 2.

EFFECTS OF CROP ROTATIONS ON SOIL QUALITY

A number of soil quality indicators such as soil aggregate stability, total and particulate soil organic carbon, microbial biomass carbon, bulk density, penetration resistance were quantified in this long-term study.

Soil aggregates are groups of soil particles that are held together more strongly than surrounding soil particles. Maintaining stability of these soil aggregates is important for conserving soil and reducing erosion. Stable aggregates also promote optimum pore space, aeration, and entry and storage of water into soil. Soil aggregates also play an important role in protecting organic matter and providing habitat to soil microorganisms and thus improve biological activity in soil which is beneficial for crop production. Soil aggregation or soil structure can promote plant root growth and crop emergence.

Soil organic carbon represents all forms of soil organic matter such as humus, the fully decomposed material with slow and continued release of plant nutrients, and more readily available fractions such as particulate organic carbon consisting of partially decomposed material and live and dead soil microorganisms. Different soil organic matter fractions influence many physical, chemical and biological properties of soil and, therefore, have a significant effect on overall soil quality and crop production.

Soil microbial biomass carbon represents the size of microbial community in soil and therefore is an important indicator of soil quality. Microorganisms make up only 1 to 8% of soil organic matter, but they can have a great impact on crop production by promoting soil aggregation and nutrient cycling.

Bulk density represents the mass of a given volume of soil and is an important indicator of soil physical quality. A low soil bulk density means a less compacted soil with good tilth that has optimum pore space and aeration required for good soil structure, water infiltration and storage, and plant root growth.

Penetration resistance is also a measure of soil compaction; a high value of penetration resistance indicates a high soil compaction which can inhibit root growth and affect water and soil quality due to increased runoff and poor soil structure.

Table 3 illustrates effects of crop rotations on soil quality indicators. Aggregate stability, measured as percent water-stable aggregates, was 1.5-3 fold higher in soils under perennial and diverse crop rotations than in soils under annual rotations of continuous corn and corn-soybean under inorganic fertilizers. Percent stable aggregates were also compared among perennials (alfalfa and red clover), double-cropped small grains (oats and wheat), summer annual crops in annual rotations (corn and soybean in continuous corn and corn-soybean rotation), and summer annual crops in perennial and diverse crop rotations (corn after alfalfa and corn after red clover). As shown in Figure 1, percent water-stable aggregates were 2-2.5 fold higher in soils under perennials, double-cropped small grains and summer annuals in perennial and diverse crop rotations compared to soils under corn and soybean in annual rotations. Similarly, perennial and diverse crop rotations also resulted in higher soil microbial biomass carbon, lower soil bulk density, and lower soil penetration resistance compared to annual rotations (Table 3).

The soil quality benefits of perennial and diverse crop rotations over the annual rotations were linked to relatively longer periods of live root activity in the perennial and diverse rotations compared to annual crop rotations. Research literature indicates that plant roots play important role in promoting stability of soil aggregates by various processes such as enmeshing soil particles, secreting glue-like substances that hold aggregates together, and supplying carbon sources that serve as food for soil microorganisms such as mycorrhizal fungi and filamentous bacteria that also promote stable aggregates in soil. Similarly, live roots also help alleviate soil compaction and reduce bulk density and penetration resistance by promoting soil structure.

In this study, in the case of continuous corn and corn-soybean rotations, crop live roots were present only from spring (after planting) to early fall (near harvesting), followed by a period of no live roots until the planting of next corn or soybean crop the following year. However, in case of perennial and diverse crop rotations, live roots were present in fall, winter and early spring months also, therefore, supplying organic carbon and promoting biological activity in soil for a longer period than the annual crop rotations. Active crop roots were present during 81% of the total period in the diverse crop rotation (corn-oats/wheat/two-year red clover), during 75% of the total length of perennial crop rotation (4 year corn-4 year alfalfa), and only 50% of the duration of annual rotations (continuous corn and corn-soybean). The longer presence of live roots of perennial and double-cropped small grains than summer annuals also resulted in less fluctuations in aggregate stability in soils under perennials and double-cropped small grains than in soils under summer annuals over the growing season (Figure 1).

Compared to inorganic fertilizers, manured treatments had higher soil aggregate stability, total soil carbon, microbial biomass carbon, and particulate organic matter carbon, which consist of relatively fresh and less decomposed organic material and is an important source of food for soil microorganisms (Table 4).

These results demonstrate that soil quality can be improved by manure applications and including perennials, winter covers, and double-cropped small grains in rotations with annual row crops and thereby promoting long periods of live root activity and reducing bare fallow periods compared to annual crop rotations of only row crops.

EFFECTS OF CROP ROTATIONS ON CORN GRAIN YIELDS

The effects of crop rotations on corn grain yields are presented in Table 5. The first- and second-year corn after alfalfa produced 12 and 5% higher grain yields than continuous corn, respectively. Similarly, corn following red clover and timothy produced 10% higher grain yields than continuous corn. Yields of corn after soybean were not statistically higher than continuous corn, but they showed a numerical gain of about 5% compared to continuous corn.

Yields increased steadily over the years at a similar rate of 4.5 bu/acre/year among all four rotations in this study. This increase is comparable or higher than National, State and County level trends in corn yields and could be due to combination of many factors including improved hybrids, transgenic traits, improved technology and management practices and favorable weather in these recent years.

There are reports that corn yields are increasing at a relatively faster rate since mid-1990s as compared to earlier decades. This increase is generally viewed as an outcome of technological advancements and improvements in seed genetics and transgenic traits. Researchers at the University of Illinois, however, advise caution in attributing these faster yield increases to the technology. Their recent analysis of long-term data on corn yields and weather conditions in Illinois, Iowa, and Indiana indicated that nearly optimum weather conditions prevailing during the last decade compared to earlier decades might have contributed to the recent greater corn yield increases compared to earlier periods.

In this study, corn yields in all four rotations varied among years during the 16-year study (Figure 2a). This variability in yields was associated with fluctuation in rainfall during the growing season. Above-normal rainfall near planting in May and limited rainfall during the critical periods of silking and grain filling in June and July affected corn yields adversely.

The variability in yields, however, differed among rotations (Figure 2). Yields were less variable and more stable in the corn following alfalfa, red clover and timothy or soybean than in the continuous corn. Figure 3 shows stability of corn yields among the four crop rotations applied with manure based on N-requirements of crops. Corn yields of each rotation were plotted against overall annual mean yields of all treatments together ranked from the poorest on left to the highest yields on right. This ranking from the poorest to the highest overall annual mean yields is a measure of environmental conditions that occurred during the 16-yr study.

In the poor-yielding years, yields were lower in continuous corn than in first-year corn after alfalfa, red clover and timothy, or soybean (Figure 3). In high-yielding years, yields in continuous corn were similar to first-year corn after alfalfa, red clover and timothy, and soybean. This suggests that when manure is applied to meet crop N requirements, continuous corn can perform equally well to the corn rotated to alfalfa, red clover and timothy, and soybean in high yielding years, but performs poorly in low-yielding years such as dry summers and wet springs. When synthetic fertilizers or P-based manure were applied, however, continuous corn yielded less than the corn after alfalfa, red clover and timothy, and soybean in low-yielding as well as high-yielding years.

The yield advantages of perennial and diverse crop rotations over continuous corn are most likely the results of multiple factors such as reduced problems of weeds, insects, and diseases. For example, corn rootworm damage has been shown to be greatly reduced by rotating corn with alfalfa compared to continuous corn even under the use of insecticides. Similarly, common diseases of corn such as gray leaf spot that occur in Pennsylvania are considerably reduced by crop rotations compared to continuous corn. Likewise, an example of effective control of summer annual weeds such as velvetleaf and foxtail with crop rotation is to follow corn with a fall- or spring-seeded small grain.

Another advantage of perennial and diverse crop rotations that contributes to yield enhancement over continuous corn is improvement in biological, chemical and physical soil quality as discussed earlier. Enhanced soil quality with the perennial and diverse crop rotations also increases the capacity of a soil to buffer against adverse climatic conditions such as drought and helps produce more stable yields than continuous corn.

The results from this long-term study on soil quality and corn yields demonstrate that perennial and diverse crop rotations with double-cropped small grains play an important role in successful crop production enterprises and soil stewardship. Crop producers can achieve high and stable corn yields and maintain soil quality by including perennials, double-cropped small grains and winter cover crops in rotation with annual row crops.

Table 1. Three fertility treatments in the long-term study at Rock Springs, Pennsylvania

Fertility type	Treatment
Inorganic	Synthetic N-P-K fertilizers
Manure	Based on crop N-requirements
	Based on crop P-requirements

Table 2. Four crop rotations in the long-term study at Rock Springs, Pennsylvania

Crop rotation type	**Crop rotation**
Annual	Continuous corn
	Corn-soybean
Perennial	4 year corn-4 year alfalfa
Diverse	Corn-oats/wheat/two-year red clover+ timothy hay

Table 3. Soil quality characteristics as affected by crop rotations initiated in 1990 under inorganic fertilizers at Rock Springs, Pennsylvania.

Crop rotation	**Soil aggregate stability (%)**[1]	**Microbial biomass carbon (µg C/g soil)**[1]	**Bulk density (g/cm^3)**[2]	**Penetration resistance (MPa)**[2]
Continuous corn	11	163	1.37	1.4
Corn-soybean	13	190	1.35	-
1st yr of the 4 yr corn -4 year alfalfa	17	294	1.26	0.8
Corn-oats/wheat/two-year red clover + timothy hay	32	396	1.28	0.8

[1]Data from 1996-2000 by:

Bucher, A.E. 2002. Soil quality characterization and remediation in relation to soil management. Ph.D. thesis. Department of Crop and Soil Sciences. The Pennsylvania State University, University Park, PA.

[2]Data from 2005-2006 by:

Thomas, J. 2008. MS Thesis. Department of Crop and Soil Sciences. The Pennsylvania State University, University Park, PA.

Table 4. Effect of inorganic fertilizers and manure applications on soil quality under continuous corn at Rock Springs, Pennsylvania (1996-2000).

	Aggregate stability (%)	**Microbial biomass carbon (μg C/g soil)**	**Total soil carbon (g/kg soil)**	**Particulate organic matter- carbon (g/kg soil)**
Inorganic fertilizers	11	160	15	2.9
N-based manure	24	370	17	4.3
P-based manure	42	480	17	4.2

Bucher, A.E. 2002. Soil quality characterization and remediation in relation to soil management. Ph.D. thesis. Department of Crop and Soil Sciences. The Pennsylvania State University, University Park, PA.

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Table 5. Average corn grain yields as affected by crop rotation over a 16-year period (1990-2005) at Rock Springs, Pennsylvania.

Crop rotation	Corn yield (bu/A)
Continuous corn	155
Corn-soybeans	162
1st yr of 4 year corn-4 year alfalfa	174
2nd yr of 4 year corn-4 year alfalfa	162
Corn-oats/winter wheat/two-year red clover + timothy hay	171

Grover, K. K., H.D. Karsten, and G.W. Roth. 2008. Corn grain yields and yield stability in four long-term cropping systems. Manuscript in preparation.

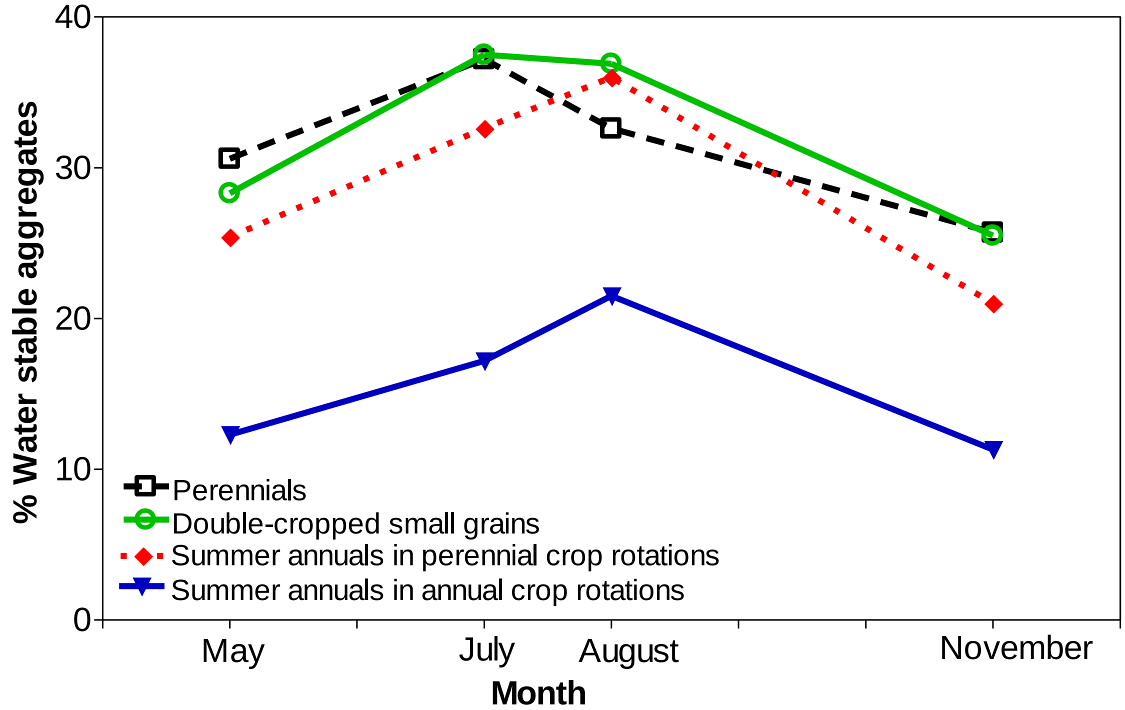

Figure 1. Soil aggregate stability as affected by crop types grown in four crop rotations during the growing season in 2005 at Rock Springs, Pennsylvania. Perennials were year 4 alfalfa and red clover; Double-cropped small grains, oats and winter wheat; Summer annuals in perennial crop rotations, year 4 corn after alfalfa and corn after red clover; Summer annuals in annual crop rotations, continuous corn, corn after soybean, and soybean after corn.

Grover, K.K., and H.D. Karsten. 2008. Water-stable aggregates in soils under four long-term cropping systems. Manuscript under review.

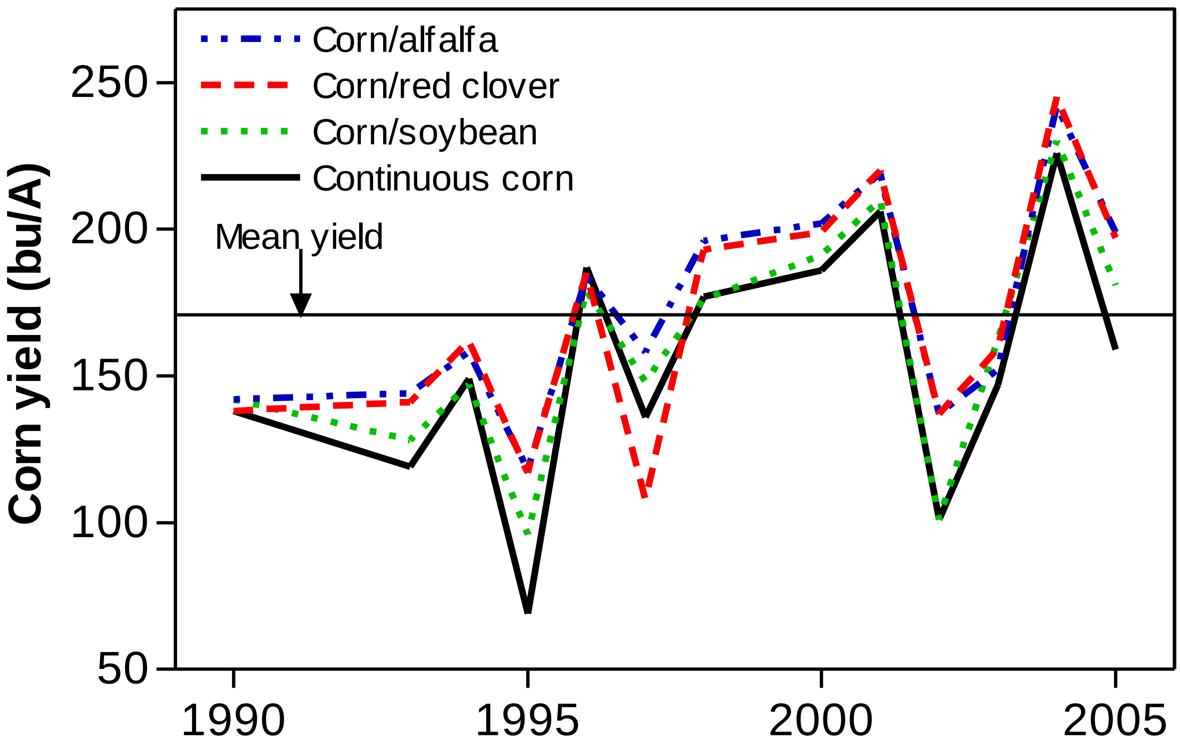

Figure 2. Year-to-to variability in corn grain yields during 1990-2005 at Rock Springs, Pennsylvania.

Grover, K. K., H.D. Karsten, and G.W. Roth. 2008. Corn grain yields and yield stability in four long-term cropping systems. Manuscript in preparation.

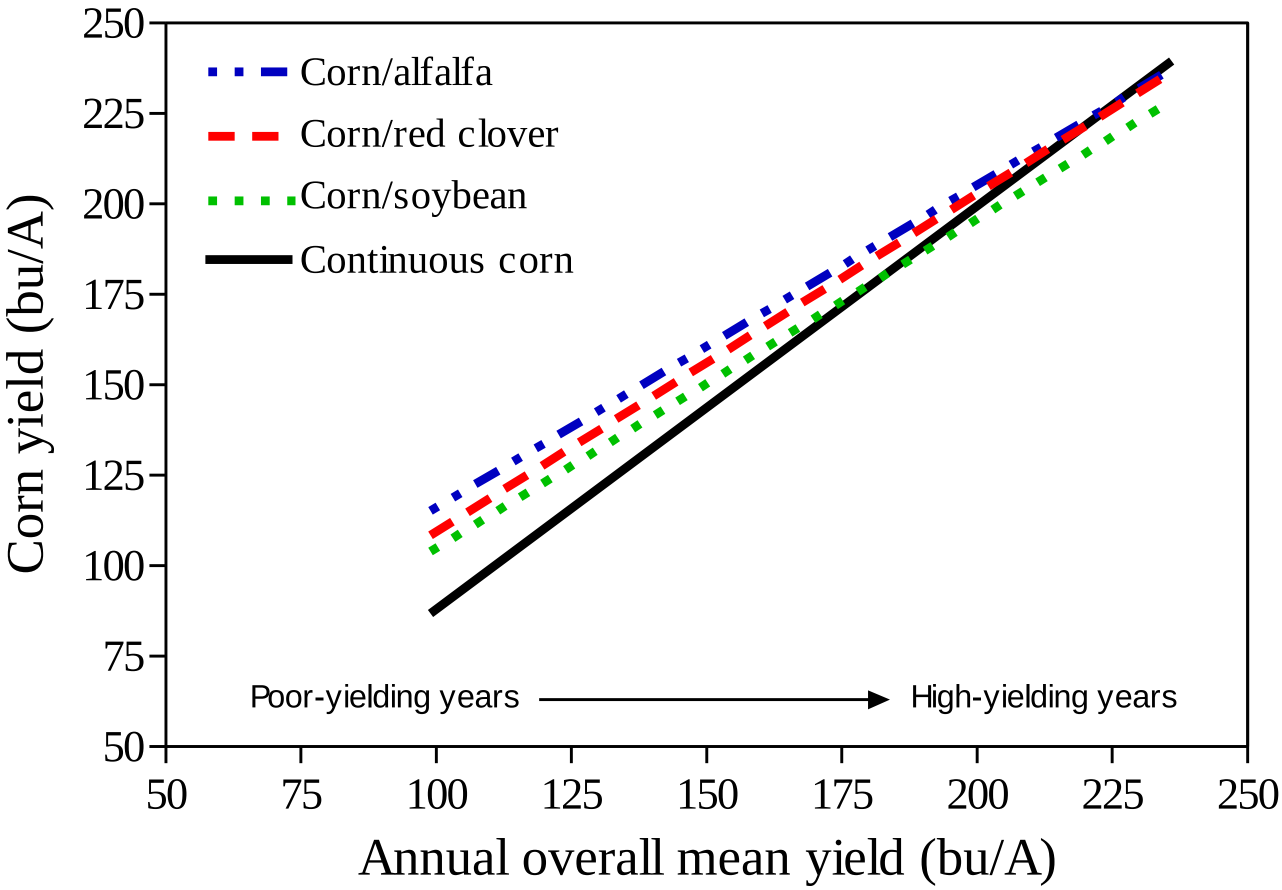

Figure 3. Stability of corn yields among four crop rotations under Nitrogen based manure applications during 1990-2005 at Rock Springs, Pennsylvania. Stability of corn yields did not differ among the four crop rotations under inorganic fertilizers and P-based manure applications.

Grover, K. K., H.D. Karsten, and G.W. Roth. 2008. Corn grain yields and yield stability in four long-term cropping systems. Manuscript in preparation.

VITAE

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PROFESSIONAL EXPERIENCE

- **Research Associate,** Department of Crop and Soil Sciences, PSU, University Park, PA (5/2008-8/2008)
- **Research & Teaching Assistant,** Department of Crop and Soil Sciences, PSU, University Park, PA (8/2003-5/2008)
- **Assistant Agronomist,** PAU, Regional Research Station, Bathinda, India (1/1996-5/97 & 6/1999-7/2003)
- **Assistant Professor of Agronomy,** PAU Farm Science Center, Gurdaspur, India (5/1997-5/1999)
- **Research Fellow,** Department of Agronomy, PAU, Ludhiana, India (11/1995-1/1996)
- **Research Assistant,** Department of Agronomy, PAU, Ludhiana, India (03/1993-11/1995)

AWARDS & HONORS

- **Outstanding Graduate Student Award,** ASA-CSSA-SSSA Northeast Branch, Montreal, QC, Canada (2008).
- **Honorary membership**, Gamma Sigma Delta, the Honor Society of Agriculture, PSU University Park, PA (2008).
- **Graduate Research & Teaching Assistantship**, Department of Crop & Soil Sci, PSU, University Park, PA (2003-07)
- **First Place**, Graduate Student Presentation Contest, Northeast ASA-CSSA-SSSA Meeting, University Park, PA (2007).
- **Gold Medal**, for Overall Best Graduate Student, College of Agriculture, PAU, Ludhiana, India (1995).

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- ASA-CSSA-SSSA
- Pennsylvania Association for Sustainable Agriculture
- Gamma Sigma Delta, the honor society of agriculture

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