The Pennsylvania State University

The Graduate School

College of Agricultural Sciences

CROP ROTATION EFFECTS ON SOIL PHYSICAL QUALITY

A Thesis in

Soil Science

by

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Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Master of Science

August 2008

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ABSTRACT

Agricultural soil management practices influence soil physical properties. Soil physical properties as affected by crop rotation were evaluated in a long- term crop rotation experiment on a Hagerstown silt loam soil (Fine, mixed, mesic Typic Hapludalf) in central Pennsylvania. Properties observed included bulk density, penetration resistance, steady-state infiltration rate, and aggregate stability. Soil properties were measured in continuous corn (Zea mays, L.), corn-soybean (Glycine max, L.) crop rotation (in the year of corn), four years of corn followed by four years of alfalfa (Medicago sativa, L.) (in the first year of corn after alfalfa, and in the fourth year of corn after alfalfa), and the corn-oat (Avena sativa, L.)-wheat (Triticum aestivum, L.)-two years of red clover (Trifolium pratense, L.) and timothy (Phleum pretense, L.) hay rotation (in the year of corn). All soils were conventionally tilled (moldboard plow followed by disk and power rotary harrow) prior to crop establishment. Fertilization was with inorganic fertilizers based on soil test recommendations. Soil physical properties in corn monoculture did not differ from those in the corn-soybean crop rotation. After the perennial crops, improved soil physical quality was observed including lower bulk density, lower penetration resistance, and higher percentage of stable aggregates (no differences in steady-state infiltration rates were observed). The improved soil physical quality after perennial crops is attributed to decreased use of tillage and longer periods of root growth per year. The research shows that rotating crops alone does not improve soil physical quality, but rather certain crops (in this case perennials) contribute to improved soil quality in a conventionally tilled system.

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CHAPTER 1: INTRODUCTION

Soil quality when applied to agroecosystems refers to the ability of the soil to support and sustain crop growth while maintaining environmental quality (Magdoff, 2001). Soil quality can be evaluated based on biological, chemical, and physical parameters. Physical properties of the soil are those soil properties that can affect root growth, seedling emergence, gaseous exchange between the soil and atmosphere, water infiltration, and water percolation through the soil profile (USDA- NRCS,1996). Criteria of soil quality include soil structural stability (tilth), root depth, internal drainage, infiltration capacity, resistance to degradation, and resilience following an episode of degradation (Magdoff, 2001).

Organic matter significantly influences soil physical properties because polysaccharides and polyuronides produced during decomposition of organic matter help promote aggregation of soil particles (Wright and Starr, 1998; Wright and Upadhyaya , 1996). Aggregation is also stimulated through growth of roots, fungal hyphae, actinobacteria, and humus. Management intended to improve soil quality can involve a combination of practices that will enhance the soil's biological, chemical and physical suitability for crop production (Magdoff, 2001). Past research suggests that soil quality can be improved by increasing crop diversity (Franco-Vizcaino, 1997), rotating perennial forage crops with annual grains (Entz, et al., 2002), rotating legume green manure crops or legume hay crops in cereal-based rotations (Campbell, et al., 2001), and replacing fallow years with other crops (Arshad, et al., 2002). Other practices shown to improve soil quality include fertilizer use and nutrient management (Campbell, et al., 2001; Magdoff, 2001), no-till

(Campbell, et al., 2001; Lal, 1999), reduced tillage (Lal, 1999), and reducing the amount of heavy equipment traffic (Magdoff, 2001; Lal, 1999).

Growing crops in a planned rotation rather than monoculture can have many advantages depending on the particular crops in rotation. Potential advantages include improving soil quality, increasing organic matter content, controlling erosion, alleviating compaction, improving infiltration and breaking pest life cycles (Magdoff and Van Es, 2000). Some crop rotations improve soil quality more than others. This is mainly a function of the quantity and quality of residue produced by the plants grown in the rotation (Hubbard et al., 1999). Crop residues from different crops may vary in decomposition rates. This diversity in decomposition rates has a large impact on nutrient availability and nutrient cycling (Swift and Anderson, 1993). Franco-Vizcaino (1997) reported with greater crop diversity higher maize yields, higher total and mineralizable nitrogen and higher total carbon. They also found trends toward lower bulk density, faster infiltration, and higher microbial biomass in the fields with greatest crop diversity.

The presence of earthworms in a soil is an indication of healthy, productive, and sustainable soils (Hubbard et al., 1999). Through their burrowing and molding activities, earthworms can improve soil aggregation and soil structure and create macropores in soil, which can improve water infiltration and gaseous exchange (Brady and Weil, 2002). Hubbard et al. (1999) observed earthworm activity under corn (Zea Mays, L.)-soybean (Glycine max, L.) and corn-wheat (Triticum aestivum, L.) rotations. They found that the corn-soybean rotation provided a higher quality food supply for the earthworms. Soybean residue has a higher nutrient value for earthworms than wheat and corn due to a lower carbon to nitrogen ratio (Hubbard et al., 1999).

Increasing the diversity of crops can also lengthen the time that roots are active (Franco-Vizcaino, 1997). Longer periods of root activity can lead to reduced erosion, increased organic matter content and water retention, and increased efficiency of nitrogen utilization in the soil (Karlen et al., 1992). A study to determine the effects of canola (Brassica napus, L.) and field pea (Pisum sativum, L.) as a replacement for summer fallow in wheat production in Alberta, Canada found that wheat yield increased an average of 10.5% when following field pea rather than fallow (Arshad et al., 2002). This study only observed crop yields and quality, but it can be speculated that replacing a fallow year with another crop improved soil quality. The advantages of having live roots in the soil and greater soil cover throughout the rotation can lead to improved soil physical properties compared with fallow. Plant tissue in the soil, alive or dead, provides critical habitat for microbes in the soil as well as protects the soil surface from rainfall and compaction (Angers and Caron, 1998).

Perennial forage crops in crop rotation lead to higher grain crop yields following forages, shifts in weed populations from summer annual weeds to perennial weeds, increased carbon sequestration, decreased nitrate leaching and improved soil quality (Entz et al., 2002). Hoyt (1990) found that even 8 years after the last year of forage production, wheat yields were still 66-114% higher than wheat yields under continuous wheat production. Forages supply a large litter base and have an extensive root system that returns some organic matter to the soil following each harvest or grazing. The organic matter returns are responsible for the greater soil carbon content found in rotations including forages. The greater amount of carbon in the soil of forage-based rotations is believed to be responsible for improved soil physical conditions (Entz et al., 2002). Forage-based systems also have far less tillage than annual cropping systems. With a reduction in tillage frequency, there is less physical destruction of aggregates, fungal hyphae, and earthworms and their habitats. Tisdall and Oades (1980) found improved soil stability from growing plants with extensive root systems and minimal cultivation. Better soil aggregation has also been found in these systems, potentially due to the higher microbial populations that produce polysaccharide mucigels that promote aggregation (Naeth et al., 1991). Not only microbial populations, but also greater abundance of earthworms, roots and fungal hyphae can improve soil aggregation and structure (Brady and Weil, 2002). In a ten year study in Saskatchewan, after conversion to no-till, an increase in bulk densities was observed in all treatments except for the crop rotation that included hay (Campbell et al., 2001). This could have been due to the aggregating effect of legume-grass roots. Campbell et al. (2001) also found that treatments containing legume green manure and legume hay had higher wet aggregate stabilities than continuous wheat.

The objectives of this research were to observe differences in soil physical quality among a variety of crop rotations. The hypothesis was that soils managed under crop rotations including a diversity of crops in rotation would have higher soil physical quality than soils managed under monoculture. Higher soil physical quality defined by this study includes lower bulk density, lower penetration resistance, higher steady state infiltration rate, and higher percentage of stable aggregates.

CHAPTER 2: MATERIALS AND METHODS

Field characteristics and management

Samples were taken in a long- term crop rotation experiment started in 1969 at the Russell E. Larson Agricultural Research Center at Rock Springs, PA (40°43’ N latitude and 77° 56’ W longitude) to evaluate crop rotation and fertility treatments on a Hagerstown silt loam soil (Fine, mixed, mesic Typic Hapludalf). Mean annual temperature was 9.4 °C and annual precipitation was 900-990 mm. The Hagerstown soil series are deep, well-drained soils formed in limestone residuum. The 0-20 cm layer is silt loam with weak fine granular structure. The 20-35 cm layer is silty clay with moderate fine and medium sub-angular blocky structure.

The experiment is set up as a randomized complete block design with 4 replications. All plots are approximately 12.2 m long by 5.5 m wide. In this study, four crop rotations were observed under the inorganic fertilizer treatment. The four crop rotations and the years the observations were made included (i) continuous corn; (ii) corn-soybean rotation, in the year of corn; (iii) four year corn, four year alfalfa (Medicago sativa, L.) rotation, in the fourth year of corn after alfalfa and iv) the first year of corn after alfalfa; (v) corn, oat (Avena sativa, L.), wheat, two year red clover (Trifolium pretense, L.) and timothy (Phleum pratense, L.) hay rotation, in the year of corn. For simplification purposes, these rotations will be further referenced using the following abbreviations: i) CC; ii) C-SB; iii) C(4)-AAAA; iv) C(1)-AAAA; v) C-O-W-HH. All soils were maintained at a pH of 7.0 and inorganic fertilizers were applied based on soil test recommendations. All plots were conventionally tilled with a moldboard plow to a depth of 18-22 cm followed by secondary tillage consisting of one pass with a disk and one pass with a power rotary harrow.

Soil analyses

Bulk density was measured with a Troxler® density gauge (Blake and Hartge, 1986) immediately after planting, six weeks after planting, and after harvest in 2005; and immediately after planting, six weeks after planting, twelve weeks after planting, and after harvest in 2006. The source rod was inserted 10 and 20 cm into the soil to measure bulk density at 0-10 cm and 0-20 cm depths. Readings were taken at two different locations in each plot. Bulk density at 10-20 cm depth was calculated as (2 x bulk density at 0-20 cm depth) **–** (bulk density at 0-10 cm depth).

Penetration resistance (Bradford, 1986) was measured after harvest in 2005, and immediately after planting and after harvest in 2006. The readings were taken with a field scout SC-900 soil compaction meter (digital cone penetrometer made by Spectrum Technologies, Inc., Plainfield, IL) with a cone diameter of 12.8 mm and cone angle of 30^o which was pushed in the soil at a constant rate of approximately 2.5 cm per second. The penetrometer recorded the resistance to a depth of 45 cm with readings at every 2.5 cm depth increment. Readings were taken from 5 locations per plot. The readings were averaged for every 5 cm depth increments resulting in 9 depth increments in a 0-45 cm profile. Penetration resistance was measured when the soil was approximately at field capacity. Water content was measured with the gravimetric method at the time of penetration resistance measurements. Two soil cores to a depth of 45 cm were extracted per plot to determine gravimetric soil moisture at intervals of 10 cm. Core samples extracted after planting utilized a manually operated soil probe to avoid soil disturbance to the newly planted corn. After harvest a hydraulic tractor-mounted Giddings® sampler was used to extract the sample. Samples were dried for approximately 72 hours at 60 degrees C to determine moisture content.

Steady-state infiltration rate was measured using a single-ring infiltrometer (Bouwer, 1986). A 35.6 cm diameter ring was kept at a constant water level (~2.5cm) using a flotation valve. Water was fed through the flotation valve from a reservoir. Volume of water infiltrated was recorded every 3 minutes in 2005 and every minute in 2006 (due to much higher infiltration rates) until infiltration rate reached a steady state. Two measurements were taken per plot in each of the two sampling years at the driest time of year. In 2005, these measurements were taken in late August and in 2006, these measurements were taken in early October.

The percent stable aggregates was measured using a wet-sieving method (Kemper and Rosenau, 1986). Two soil cores to a depth of 40 cm were extracted per plot immediately after planting and after harvest in 2006. A portion of the core samples extracted for determining gravimetric water content was used for measuring percent stable aggregates. Core samples extracted after planting utilized a manually operated soil probe to avoid soil disturbance to the newly planted corn. After harvest a hydraulic tractor-mounted Giddings® sampler was used to extract the sample. Samples were separated into 10 cm sections and air dried prior to grinding and dry sieving to isolate the 1-2 mm aggregate size. The samples were then placed on a 0.25 mm sieve and a dunking apparatus was used to dunk the samples into distilled water for three minutes. Those aggregates that remained were deemed stable. Aggregation was corrected for sand-size particles (1-2 mm) via sonic-cell dispersion.

Data were analyzed using a mixed procedure (PROC MIXED) in SAS version 9.1.

CHAPTER 3: RESULTS AND DISCUSSION

Bulk Density

In 2005, soil bulk density was affected by crop rotation (Table 1) and depth, and there was an interaction between depth and date (Figure 1a). In 2006, soil bulk density was not affected by crop rotation, but it varied by date (Table 1) and there was an interaction between depth and date (Figure 1b) and between crop rotation and date (Table 1).

In 2005, there was no difference in bulk density in the 0-20 cm depth between the CC, C-SB, C(4)-AAAA and C(1)-AAAA rotations. CC, C-SB, and C(4)-AAAA had higher bulk density than the C-O-W-HH rotation. Bulk density in the C(1)-AAAA rotation did not differ from any of the other rotations.

In 2006, there was no difference in bulk density between crop rotations, however there was an interaction effect between crop rotation and the time of year the measurement was taken. After planting soil bulk density was highest under the annual crop rotations (CC, C-SB) while C-O-W-HH had the lowest soil bulk density of the rotations. The bulk density in both four year corn, four year alfalfa rotations was intermediate between C-O-W-HH and the annual crop rotations. At six weeks after planting C(4)-AAAA had lower soil bulk density than C-SB. All other rotations had a bulk density that was intermediate between these two rotations. At twelve weeks after planting C-SB and C(4)-AAAA had higher bulk density than C(1)-AAAA. The bulk density of CC and C-O-W-HH rotations was intermediate. After harvest the annual crop rotations had higher soil bulk density than C(4)-AAAA. The other rotations had a bulk density that was intermediate between these values.

In both years, bulk density was lower at the 0-10 cm depth than at the 10-20 cm depth under all the rotations. In 2005 bulk density increased over the growing season at the 0-10 cm depth, while it decreased at the 10-20 cm depth (Figure 1a). In 2006 we observed bulk density increasing at both depths over the growing season (Figure 1b).

CC and C-SB rotations included only annual crops and were tilled every year. Tillage has been shown to lead to higher soil bulk densities when used year after year due to soil structure destruction, use of heavy equipment, and compaction taking place just below the tillage tool. A four year corn, four year alfalfa rotation includes a perennial crop in rotation in four out of eight years and therefore eliminates tillage half of the years, however by the fourth year of corn after alfalfa, as observed in 2005- the soil has been influenced by four years of annual crop production and has shown high bulk densities similar to that of the annual crop rotations.

The rotation resulting in the lowest bulk density was the C-O-W-HH rotation. There are several differences between this and the other rotation containing a perennial crop that could explain this. One difference is the type of perennial in rotation. The four year corn, four year alfalfa rotations include alfalfa, a deep tap-rooted leguminous perennial crop. C-O-W-HH contains a mixture of a red clover legume with a grass. The difference in root structure could explain this difference in bulk densities. The dense, fibrous rooting system of the grass in the upper 20 cm may have led to the lower bulk density under this rotation. Hubbard et al. (1999) found that certain crop rotations improved soil quality more than others and that observation was mainly a function of the quantity and quality of residues produced. C-O-W-HH also had a higher diversity of crops in rotation (five crop types versus only two crop types in the four year corn, four year alfalfa rotations). Franco-Vizcaino (1997) similarly found trends towards lower bulk density under higher diversity crop rotations.

C(1)-AAAA and C-O-W-HH are in their first year of corn following a perennial crop and may have better soil physical properties that are associated with a longer period of root activity in the soil. Root activity leads to better soil aggregation, which results in more pore space and lower bulk densities. Following tillage, the beneficial effects of the perennial crop were not as evident by the end of the growing season in 2006, and at this point in the growing season these rotations displayed very similar bulk densities to those of CC and C-SB.

Low bulk density at shallow depth early in the growing season may have been due to soil loosening effects of tillage, while the greater bulk density at the deeper depth may have been the result of the compacting effect of the tillage implement. During the growing season, reconsolidation of the shallow surface soil took place, while some alleviation of bulk density by biological activity may have occurred at the deeper depth.

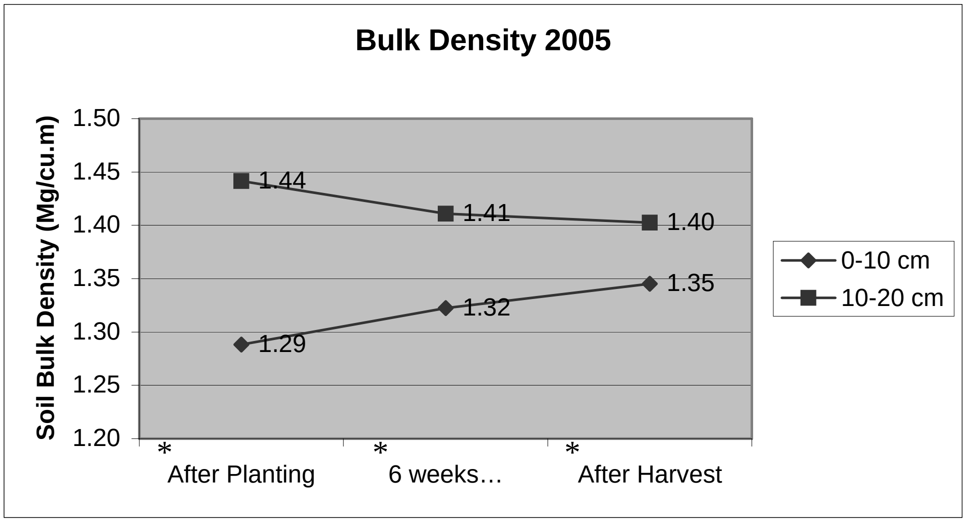
Table 1- Soil Bulk Density (Mg/m^3) in 0-20 cm depth in 2005 and 2006.

2005					
	After Planting	**6 weeks…**		**After Harvest**	**2005 Mean**
CC	1.39	1.40		1.40	1.40 *B*
C-SB	1.39	1.42		1.41	1.40 *B*
C(4)-AAAA	1.35	1.39		1.38	1.37 *B*
C(1)-AAAA	1.36	1.32		1.37	1.35 *AB*
C-O-W-HH	1.32	1.31		1.31	1.31 *A*
Rotation Mean	1.36	1.37		1.37	
2006					
	After Planting	**6 weeks…**	**12 weeks…**	**After Harvest**	**2006 Mean**
CC	1.32 bc	1.36 ab	1.31 ab	1.46 b	1.36
C-SB	1.36 c	1.37 b	1.35 b	1.45 b	1.38
C(4)-AAAA	1.25 ab	1.29 a	1.35 b	1.36 a	1.31
C(1)-AAAA	1.25 ab	1.31 ab	1.27 a	1.44 ab	1.31
C-O-W-HH	1.24 a	1.31 ab	1.28 ab	1.39 ab	1.30
Rotation Mean	1.28 A	1.33 B	1.31 B	1.42 C	

CC= Continuous Corn; C-SB= Corn-Soybean crop rotation in the year of corn; C(4)-AAAA= four years corn- four years alfalfa crop rotation, fourth year of corn after alfalfa; C(1)-AAAA= Four years corn- four years alfalfa crop rotation, first year of corn after alfalfa; C-O-W-HH= Corn-Oat-Wheat- two years Red Clover Hay crop rotation in the year of corn. In 2005, sampling date and sampling date x rotation effects were not significant. In 2006, main rotation effects were not significant.

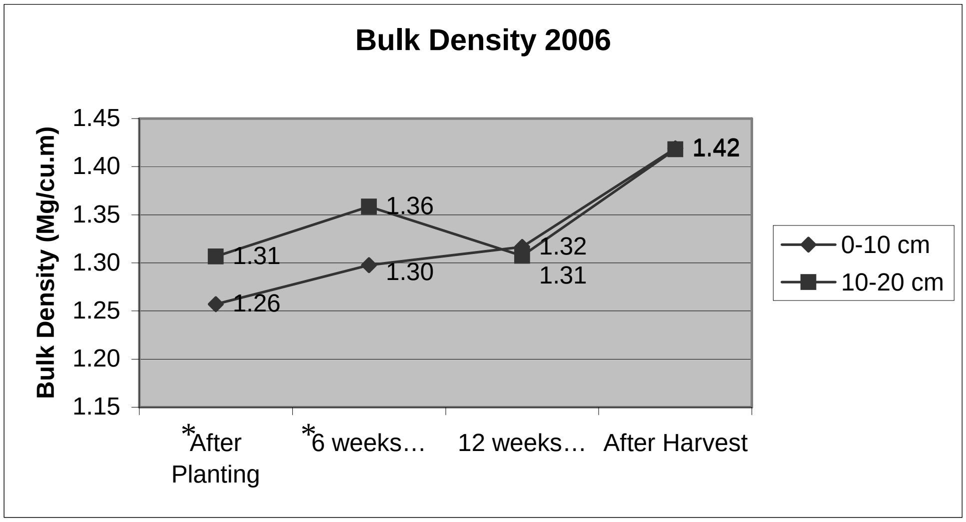
Separation of means is within years. Rotation means over all four sampling dates are not significantly different if followed by the same italic capital. Sampling date means over all five rotations are not significantly different if followed by the same capital letter. Means of one crop rotation at one depth are not significantly different if followed by the same lowercase letter.

Figure 1a- Soil bulk density (Mg/m^3) from planting to harvest at 0-20 cm depth in 2005 (average all crop rotations).



*** indicates bulk density at given date was significantly different between depths ($p<0.05$).**

Figure 1b- Soil bulk density (Mg/m^3) from planting to harvest at 0-20 cm depth in 2006 (average all crop rotations).



*** indicates bulk density at given date was significantly different between depths (p<0.05).**

Penetration Resistance

Penetration resistance was not influenced by crop rotation at any of the three sampling periods (after harvest 2005, after planting 2006, and after harvest 2006). In 2006 there was an interaction between crop rotation and the date of measurement (Figure 2).

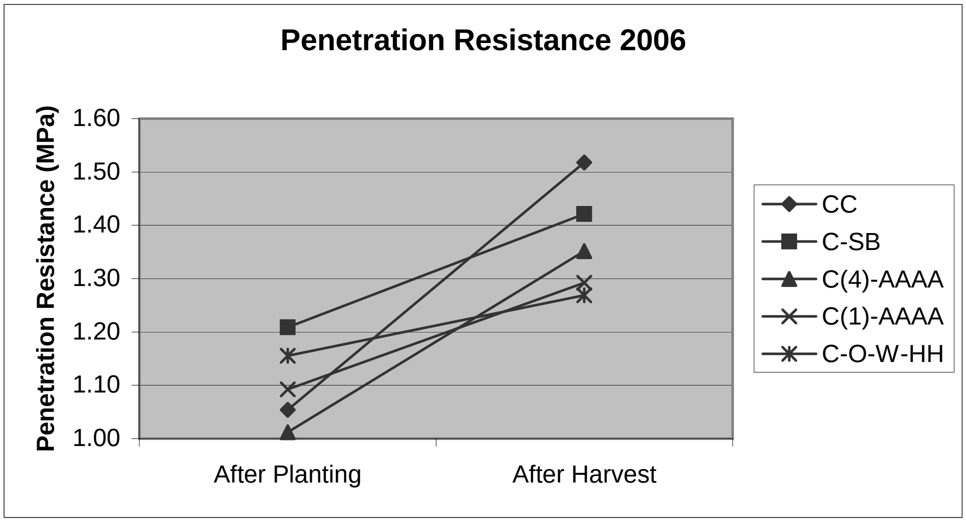
In 2006 the penetration resistance in all crop rotations observed increased from planting until harvest, except that the increase was not significant in the case of the C-O-W-HH rotation. The increase seemed to be greatest in the CC and C(4)-AAAA rotations, smallest in the C(1)-AAAA and C-O-W-HH rotations, whereas the increase in penetration resistance in the C-SB rotation was intermediate.

Measurements taken in 2006 also show an interaction between depth and date of measurement (Figure 3). From the surface to approximately 24 cm, penetration resistance increased from planting until after harvest. Below this depth, there is no change between the two dates of measurement.

The positive effect of the perennial crops in the rotation on soil physical quality in the following crop is also evident from penetration resistance data. The C-O-W-HH rotation seemed to cause the greatest reduction in penetration resistance, whereas alfalfa crop had not as great an effect. This may have been a function of the type of perennial rather than simply a reduction in frequency of tillage. The red clover and timothy grass-legume mixture has the benefits of a fibrous grass root system. The benefit of the fibrous root system may have led to these soils becoming less influenced by tillage and better able to maintain low penetration resistance through the growing season. Soil structure in all other rotations including the four year corn, four year alfalfa rotations appeared to be more greatly affected by tillage, resulting in an increase in penetration resistance from planting to harvest.

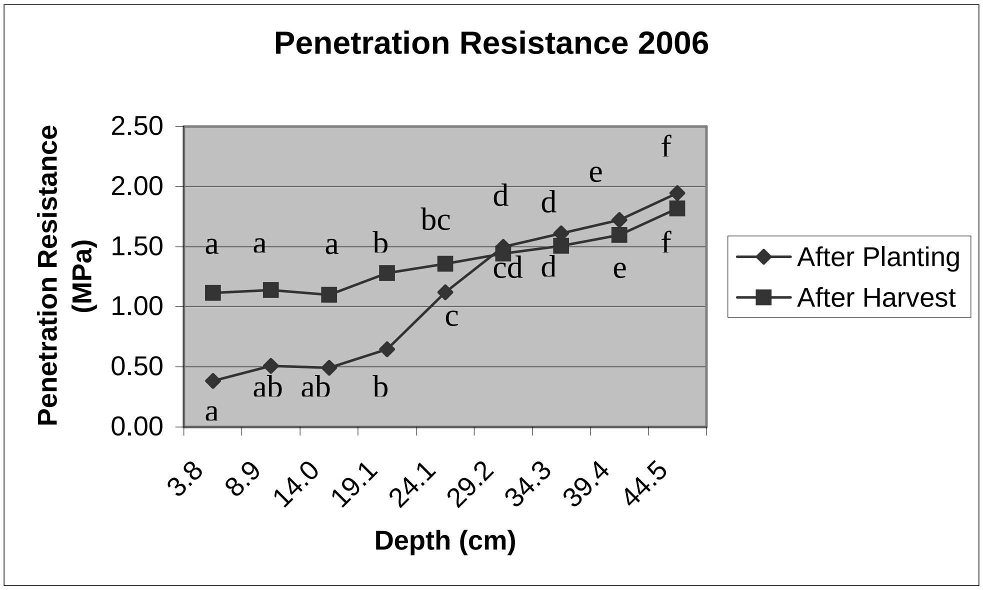
The increase in penetration resistance in the upper part of the soil profile can be attributed to the tillage effect of temporarily loosening the soil. The depth of plowing was approximately 18 to 22 cm, below which tillage would not influence penetration resistance, except if it would have compacted the soil below the tillage implement. In our case there was no clear indication of a plow pan caused by the moldboard plow or other tillage implement.

Figure 2- Average penetration resistance (0-45 cm depth) in corn year of five crop rotations from planting to harvest in 2006.



CC= Continuous Corn; C-SB= Corn-Soybean crop rotation in the year of corn; C(4)-AAAA= four years corn- four years alfalfa crop rotation, fourth year of corn after alfalfa; C(1)-AAAA= Four years corn- four years alfalfa crop rotation, first year of corn after alfalfa; C-O-W-HH= Corn-Oat-Wheat- two years Red Clover Hay crop rotation in the year of corn.
All crop rotations except C-O-W-HH had significantly higher penetration resistance after harvest than after planting ($p<0.05$).

Figure 3- Soil penetration resistance at planting and harvest time in 2006 at 0-45 cm depth.



Separation of means is within each sampling date.
Penetration resistance values at one sampling date were not significantly different if followed by the same letter (p<0.05).

Steady-state Infiltration Rate

Crop rotation did not affect steady-state infiltration rate in 2005 or 2006. However, a much higher steady-state infiltration rate was observed in 2006 compared to 2005 in all crop rotations. In 2005, the average steady-state infiltration rate for all rotations was 8 cm/hr. In 2006, the average steady-state infiltration rate for all rotations was 63 cm/hr. These measurements were planned at the driest time of the year. In Central Pennsylvania, the driest period is usually July or early August. In 2005, the measurements were taken at that time of year. In 2006, however, there were large amounts of rain occurring in August, which resulted in the measurements being postponed. The soil never did revert to the same conditions as in 2005. The 2006 measurements were taken at the beginning of October. The higher rates observed in 2006 can possibly be related to the soil and weather conditions. In October, the soil was moist and the air temperatures were lower than in August. One potential explanation could be that these conditions influenced the activity of earthworms. With a greater abundance of earthworms in the soil, there is a greater proportion of macropores, which can allow for higher infiltration rates (Brady and Weil, 2002). We observed small swirling taking place in the infiltration rings in 2006, which seemed to be always above nightcrawler burrows.

The alfalfa crop has a deep-rooted taproot, which upon decay leaves macropores that can allow for higher infiltration rates. The crop rotations containing alfalfa were expected to have higher infiltration rates than those that do not include alfalfa. Soils under management including perennial crops are typically well- aggregated soils due to lower frequency of tillage and greater periods of live root growth. Well-aggregated soils contain more pore space and can provide for higher rates of infiltration. When tillage is used, stable aggregates are destroyed and there is less pore space available for water to infiltrate. Contrary to these expectations, there were no differences observed among the crop rotations. A possible reason for the lack of significance may have been the high variability in the measurements.

Aggregate Stability

Aggregate stability was measured after harvest in 2006. Crop rotation and depth affected aggregate stability, and there was a crop rotation x depth interaction.

The rotations including perennial crops had greater aggregate stability, which was measurable the year after termination of the perennial crop (C(1)-AAAA, and C-O-W-HH), and also four years after termination of the perennial crop (C(4)-AAAA) (Table 2).

At the 0-10 cm depth the same observations were made as with the average depth described previously. At the 10-20 cm depth C(1)-AAAA and C-O-W-HH led to the highest percent stable aggregates, but C(4)-AAAA resulted in similar percent stable aggregates to that of CC. At this depth C-SB resulted in the lowest percent stable aggregates. There was no difference in percent stable aggregates among the rotations at 20-40 cm depths.

Again, we see the benefits of including a perennial crop in rotation. Longer periods of root activity in the soil associated with perennial crops led to better aggregation of the soil. The destructive effect of tillage on stable aggregates has been observed in other studies, however we did not make the same observation. In the case of aggregate stability we see the benefit of a perennial crop (alfalfa) still apparent four years after the termination of the perennial crop (C(4)-AAAA). Hoyt (1990) similarly observed benefits of a perennial crop even eight years after the termination of the perennial crop.

Soils under any of the rotations would be expected to have low percent stable aggregates at depth due to the lack of living roots and the weight of overlaying soil, however those that included a perennial crop displayed low percent stable aggregates throughout the entire soil profile.

Table 2- Effect of crop rotation on percent stable aggregates (0-40 cm depth) immediately after harvest in 2006

	0-10 cm	10-20 cm	20-30 cm	30-40 cm	Depth Mean
CC	30 a	34 ab	26	29	30 *A*
C-SB	26 a	33 a	30	34	31 *A*
C(4)-AAAA	46 b	46 bc	39	30	40 *B*
C(1)-AAAA	49 b	49 c	47	33	45 *B*
C-O-W-HH	56 b	51 c	38	27	43 *B*
Rotation Mean	41 C	42 C	36 B	31 A	

CC= Continuous Corn; C-SB= Corn-Soybean crop rotation in the year of corn; C(4)-AAAA= four years corn- four years alfalfa crop rotation, fourth year of corn after alfalfa; C(1)-AAAA= Four years corn- four years alfalfa crop rotation, first year of corn after alfalfa; C-O-W-HH= Corn-Oat-Wheat- two years Red Clover Hay crop rotation in the year of corn.
Rotation effects were not significant at 20-40 cm depth.
Means of rotations over all depths are not significantly different if followed by the same italic capital ($p<0.05$). Means of rotations for one depth are not significantly different if followed by the same capital letter ($p<0.05$). Means of one crop rotation at one depth are not significantly different if followed by the same lowercase letter ($p<0.05$).

CHAPTER 4: CONCLUSIONS

It can be concluded that crop rotation diversity alone did not solely influence soil physical quality, but rather the influence was derived from the crops that were grown in the rotation and the management practices associated with those crops.

Soil physical properties, particularly bulk density and percent stable aggregates, under CC and C-SB, the two rotations containing only annual crops were very similar. The influence of crop rotation alone in the case of C-SB was not enough to improve soil physical properties. Both corn and soybeans are annual crops and are tilled prior to establishment in every year. Tillage has been shown to destroy stable soil aggregates, which can lead to compaction and higher bulk density and penetration resistance. In addition, actively growing annual crop roots occupy the soil for only a portion of the year in comparison to perennial crops, leading to less favorable effects on soil physical quality.

Soils under the rotations including perennial crops (C(4)-AAAA, C(1)-AAAA, and C-O-W-HH) had more favorable soil physical properties than soils under the annual crop rotations. This is similar to observations made by Entz et al. (2002). When perennial crops are grown in a rotation, tillage is eliminated several years in the rotation. In the absence of tillage, the period of root activity in the soil is lengthened. Root activity, particularly legume root activity (in this case alfalfa and red clover) leads to better soil aggregation, which gives way to more pore space, less compaction, and lower bulk density. Inclusion of grass with a legume in rotation (in the case of red clover and timothy hay) can also promote lower bulk density due to its dense fibrous root system. Generally lower bulk densities and higher percentage of stable aggregates were observed under these rotations; however, there was an exception in the case of C(4)-AAAA influence on soil bulk density in 2005. C(4)-AAAA actually led to similar bulk density to the annual crop rotations. One explanation could be that by the fourth year of corn after alfalfa, the benefits of the perennial legume crop on bulk density are less apparent. The soil physical quality response to this rotation was not observed in some of the 2006 bulk density measurements (after planting and after harvest) or in the percent stable aggregates. In each of these cases we saw the physical properties of soils managed under the C(4)-AAAA rotation did not differ from the physical properties of soils managed under C(1)-AAAA and C-O-W-HH rotations.

While the most diverse crop rotation (C-O-W-HH) did exhibit superior soil physical quality in some cases, in other cases it was no different than the other rotations containing perennial crops. Improved soil physical properties were observed as the result of including perennial crops in rotation. Perennial crops included in rotation provide the benefit of reducing the frequency of tillage in a conventionally tilled system. Other benefits of perennial crops, particularly legume crops, were discussed previously and include a longer period of root activity in the soil leading to better soil aggregation.

With the increasing adoption of no-tillage the question arises: do the observed effects also apply in no-tillage systems? Tillage essentially homogenizes the soil prior to planting, and we therefore believe effects of crop rotations on soil physical quality would be even greater in no-till system. There is evidently a need for future research in the area of crop rotations in no-till systems.

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