EFFECT OF CROP PRODUCTION SYSTEMS ON SOIL ORGANIC CARBON CONTENT AND ON SOME SOIL PROPERTIES

THESIS OF PHD DISSERTATION

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Gödöllő

2006

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Science: Soil science, agrochemistry, environmental chemistry

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INTRODUCTION

Importance and current status of the topic

Over the past 150 years, the amount of carbon-dioxide in the atmosphere has increased by 30 %. The atmospheric concentration of carbon-dioxide and other greenhouse gases are strongly linked to global warming. Numerous researchers have investigated the potental impact of climate change also in Hungary (Németh et al. (1998, 2002), Faragó and Kerényi (2003), Faragó et al. (2004), Várallyay (2004)) and the „Változás–Hatás-Válasz Program" (VAHAVA, 2006) and emphasized the importance of preventing the negative consequences.

One possibility to reduce atmospheric carbon-dioxide is by carbon sequestration into the soil. The carbon stored in soils is nearly three times that in the aboveground biomass and approximately double that in the atmosphere (Eswaran et al., 1993).

Depending on the land use soils can act as sinks (absorbers) or as sources (emitters) of the greenhouse gases. Conventional tillage has frequently been associated with losses in soil organic carbon, but less intensive tillage systems (such as no-till) have been effective in helping soils act as a carbon sink. However, most of these carbon studies have focused on the plow layer and did not account for potential changes at deeper depths (West and Post, 2002), and also estimations for a given area are done based on the upper 30 cm depth.

Objectives

Although the purpose of most carbon studies is related to impacts of global climate change, a better understanding of management-induced changes has benefits far beyond the current objectives of carbon sequestration projects. In sustainable agricultural production, the maintenance of soil organic matter quantity and quality is of key importance and rebuilding organic matter levels is a slow and difficult process. Beside the main objective of my doctoral research – investigation of the soil's ability to sequester carbon – I have determined other soil physical and chemical parameters as well, which help the complex understanding of the effect of different tillage and rotation systems on the soil.

The objectives of the research were to:

- determine the impact of conventional tillage (moldboard plowing), a reduced tillage system (chisel plowing), the change of the tillage system, and conservation tillage (no-till) on soil organic carbon and total nitrogen content and depth distribution in continuous corn and soybean-corn rotations in each sampling depth and to a 1 m depth,
- investigate the impact of the different tillage and rotation systems on some soil physical properties related to the organic matter status of the soil (bulk density, aggregate stability and water retention),
- investigate the impact of the different tillage and rotation systems on soil nutrient availability and soil pH,
- determine similarities and differences in the elemental and molecular composition of the humic and fulvic acid fractions extracted from composite soil samples representing the different tillage and rotation systems.

MATERIALS AND METHODS

Sampling sites

Two sampling sites were chosen for the purpose of this study. Both experimental sites are located at the Agronomy Center for Research and Education of Purdue University near West Lafayette, Indiana (USA). The soil is dark-colored, has high organic matter content (appr. 4 % in the upper 30 cm depth) and high clay content. It is a chernozem meadow soil - Typic Endoaquolls according to the U.S. Taxonomy (Keys to Soil Taxonomy) (Soil Survey Staff, 2006) and Gleyic Chernozem according to the World Reference Base for Soil Resources (IUSS working group, 2006) – with clay loam structure.

The **Purdue Long-term Tillage Experiment** has been conducted since 1975. The experiment is a randomized complete block in a split-plot design with treatments replicated four times. From the treatments moldboard plow (PL) and no-till (NT) systems were compared in corn (*Zea mays* L.) monoculture (CC) and in soybean (*Glycine max* (L.) Merr.)-corn rotation (BC).

Fall moldboard plowing was done to a depth of 20 to 25 cm. No-till planting was done with standard seed disk openers (West et al., 2002).

The **Purdue - Integrated Pest Management Study** was initiated in 1980. A split-plot design with four replications was utilized (Sváb, 1981; Martin et al., 1991; Schreiber, 1992). The following tillage treatments in continuous corn were sampled:

- No-till (NT) – no-till in 1980-2003 (for 24 years)
- Short-term no-till (ST-NT) – moldboard plow in 1980-1996 (for 17 years)
  chisel plow in 1997 (for 1 year)
  no-till in 1998-2003 (for 6 years)
- Short-term chisel plow (ST-CH) – moldboard plow in 1980-1996 (for 17 years)
  chisel plow in 1997-2003 (for 7 years)
- Chisel plow (CH) – chisel plow in 1980-2003 (for 24 years).

Measured parameters

Chemical measurements

- Organic carbon (OC) and total nitrogen (N) concentration (g/kg) (by dry combustion)
- Organic matter (OM) concentration (%) and soil C/N ratio
- Organic carbon and total nitrogen content (t/ha) to 1 m depth and in equivalent soil mass
- Soil phosphorus (P), potassium (K), calcium (Ca) concentration (ppm) and soil pH (H_2O)
- Elemental composition of the extracted and fractionated humic materials (C, N, H, O concentration (%), C/N ratio, H/C ratio and humic acid – fulvic acid ratio (HA/FA ratio))
- Molecular composition of the extracted and fractionated humic materials (Fourier transform infrared spectroscopy).

Physical measurements

- Bulk density (BD) (g/cm^3)
- Macroaggregate stability by wet sieving (mean weight diameter (MWD) determination)
- Microaggregate stability by rheology (Vane rotor)
- Water retention on undisturbed samples (pF 1,7 ; pF 2 ; pF 2,5), and on disturbed samples (pF 4,2) (volumetric and gravimetric water content).

Statistical analysis

Analysis of variance (ANOVA) was performed within depth and differences among means were tested using the least significant difference test (LSD) at α level of 0.05 (SAS Institute, Inc., 2002). Statistical analysis comprised of calculating the standard deviation of the means for the analysis of humic materials.

RESULTS AND DISCUSSION

The most important findings of my doctoral research will be presented in the followings.

ORGANIC CARBON, TOTAL NITROGEN, C/N RATIO AND BULK DENSITY

Purdue Long-term Tillage Experiment

Tillage treatments had more impact on carbon and nitrogen storage, and bulk density of the soil (Table 1., Figures 1-2.), than crop rotation treatments (Table 2., Figures 3-4.). Interactions of rotation × tillage were consistently insignificant.

Table 1. Tillage treatment effects (averaged for two crop rotations) on organic carbon, organic matter, total nitrogen concentrations, C/N ratio and bulk density at multiple depth increments to a 1 m sampling depth

Depth (cm)	OC (g/kg)			OM (%)			N (g/kg)			C/N ratio		BD (g/cm^3)		
	NT		PL	NT		PL	NT		PL	NT	PL	NT		PL
0-5	35.7	**	23.9	6.2	**	4.1	2.8	**	1.9	14.9	15.1	1.26	**	1.13
5-15	26.6	*	24.1	4.6	*	4.1	2.1	*	1.9	14.8	15.4	1.37	**	1.16
15-30	22.9		24.5	3.9		4.2	1.8		1.9	14.9	15.4	1.40	**	1.16
30-50	11.6	*	15.2	2.0	*	2.6	1.0	*	1.3	13.8	14.5	1.44		1.45
50-75	4.7		5.1	0.8		0.9	0.6		0.6	14.1	14.9	1.42		1.44
75-100	3.1	*	3.5	0.5		0.6	0.4		0.3	12.4	13.3	1.55		1.50

* Significant differences between two tillage systems at α=0.05
** Significant differences between two tillage systems at α=0.01
NT – no-till PL – moldboard plow

The organic carbon and total nitrogen content (t/ha) was higher for no-till than plow in the 0-30 cm depth, but in the 30-50 cm layer plow stored a significantly higher amount of both organic carbon and total nitrogen.

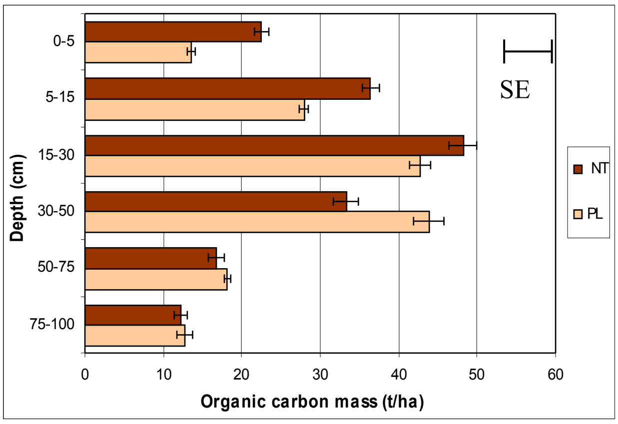

Figure 1. Organic carbon content per unit area for two tillage systems at multiple depth increments to a 1 m sampling depth

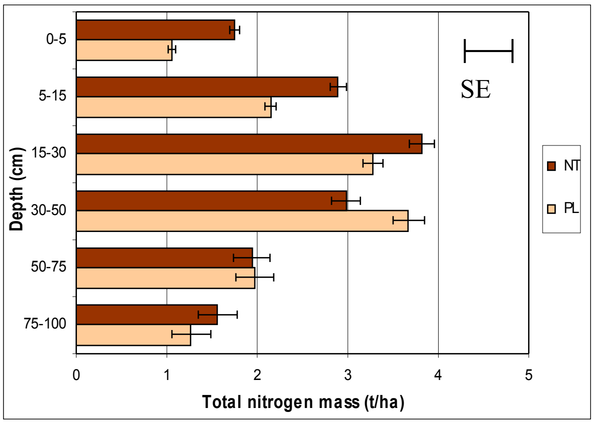

Figure 2. Total nitrogen mass per unit area for two tillage systems at multiple depth increments to a 1 m sampling depth

Table 2. Rotation effects (averaged for two tillage treatments) on organic carbon, organic matter, total nitrogen concentrations, C/N ratio and bulk density at multiple depth increments to a 1 m sampling depth

Depth (cm)	OC (g/kg)			OM (%)		N (g/kg)		C/N ratio		BD (g/cm^3)	
	CC		BC	CC	BC	CC	BC	CC	BC	CC	BC
0-5	30.7		29.0	5.3	5.0	2.3	2.3	15.4	14.6	1.18	1.21
5-15	25.7		24.9	4.4	4.3	1.9	2.0	15.8	14.4	1.24	1.28
15-30	24.4		23.1	4.2	4.0	1.8	1.9	15.9	14.4	1.30	1.27
30-50	13.8		13.0	2.4	2.2	1.1	1.2	15.3	13.0	1.44	1.45
50-75	5.0		4.8	0.9	0.8	0.5	0.6	17.2	11.9	1.43	1.43
75-100	2.9	*	3.8	0.5	0.7	0.3	0.4	15.7	10.5	1.53	1.52

* Significant differences between two rotations at α=0.05
CC – continuous corn BC – soybean-corn rotation

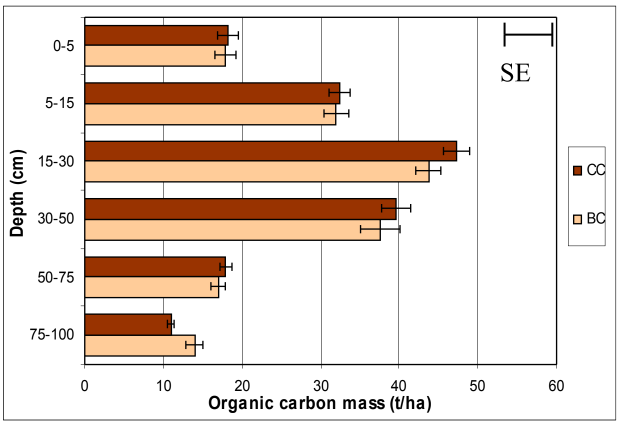

Figure 3. Organic carbon mass per unit area for two rotation systems at multiple depth increments to a 1 m sampling depth

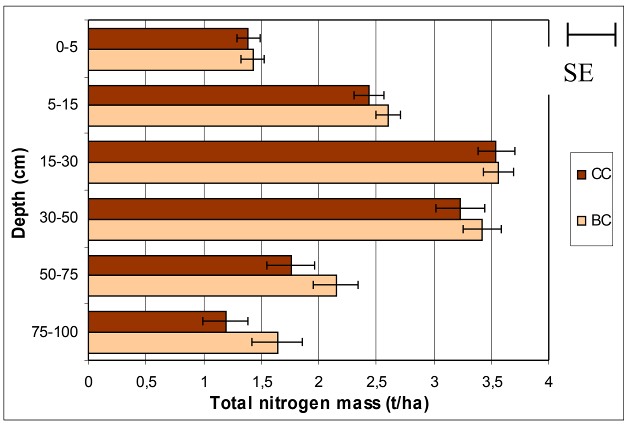

Figure 4. Total nitrogen mass per unit area for two rotation systems at multiple depth increments to a 1 m sampling depth

Purdue - Integrated Pest Management Study

Organic carbon, organic matter and total nitrogen concentrations decreased with depth increment in all tillage systems. Bulk density increased with depth, but tillage system differences were not significantly different at any depth interval. The overall trends in mass of OC and total N sampled to 1 m depth on a mass per unit area and on equivalent soil mass basis are summarized below:

The observed trends on a mass per unit area basis to 1 m depth were as follows.
For organic carbon mass (t/ha): ST-NT = NT > ST-CH > CH
For total nitrogen mass (t/ha): ST-CH > NT > ST-NT > CH

The observed trends on an equivalent soil mass basis were as follows.
For organic carbon mass (t/ha): NT = ST-NT > ST-CH > CH
For total nitrogen mass (t/ha): ST-CH > NT > ST-NT > CH

SOIL PHOSPHORUS, POTASSIUM, CALCIUM CONCENTRATION AND PH

Analyses of soil pH and nutrient concentrations can potentially provide perspectives on possible differences in plant and root development among tillage and rotation systems and, consequently, in the amount of residue returned to the soil and in the growth and vertical stratification of the root system.

Purdue Long-term Tillage Experiment

Tillage effects were more pronounced than rotation effects, and the interactions between tillage and rotation were never significant for any of the nutrient parameters measured. Tillage system effects are shown in Table 3.

Table 3. Tillage system effects (averaged for two rotations) on soil pH and phosphorus, potassium and calcium concentrations at multiple depth increments to a 1 m sampling depth

Depth	pH (H_2O)			P (ppm)			K (ppm)			Ca (ppm)		
(cm)	NT		PL	NT		PL	NT		PL	NT		PL
0.5	7.05	**	6.65	161.7	**	52.5	527.4	**	153.9	2949		3122
5-15	5.94	**	6.74	100.8	**	47.7	225.9	**	146.7	2603	**	3138
15-30	5.39	**	6.78	59.1		54.6	115.5	**	181.3	2236	**	3176
30-50	6.38		6.61	12.6	*	22.4	100.6	**	121.5	3239		3224
50-75	6.99		7.02	5.5	*	4.8	96.4		97.1	3056		3092
75-100	7.51		7.48	6.0	*	4.9	90.1		89.5	2676		2787

* Significant differences between two tillage systems at α=0.05
** Significant differences between two tillage systems at α=0.01
NT – no-till PL – moldboard plow

Purdue - Integrated Pest Management Study

Soil phosphorus and potassium concentrations decreased with depth in all tillage treatments. Although no-till had somewhat lower pH levels, there were no significant tillage effects on pH.

Soil P and K concentrations were above the accepted critical levels in the Tri-State Fertilizer Recommendations (Vitosh et al., 1995) and probably did not impair the relative crop biomass production in any of the tillage systems.

AGGREGATE STABILITY

Macroaggregate stability

Macroaggregate stability was significantly influenced by tillage (Figure 5.), rotation (Figure 6.) and their interaction at certain depths. Macroaggregate stability was consistently higher in no-till than in plow at all depth intervals. As for the rotation effect, continuous corn had higher mean weight diameter than the soybean-corn rotation in all depth increments.

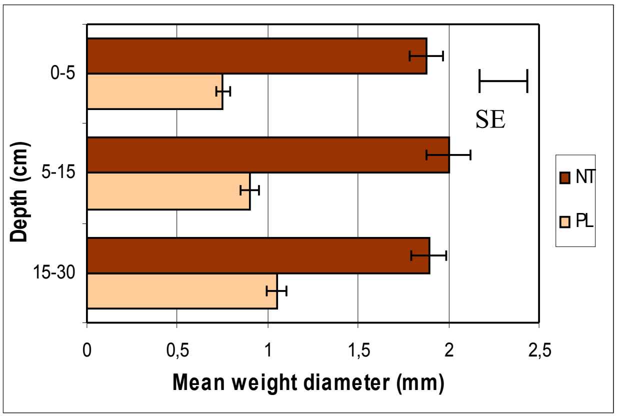

Figure 5. Tillage effects on aggregate mean weight diameter at multiple depth increments to 30 cm depth

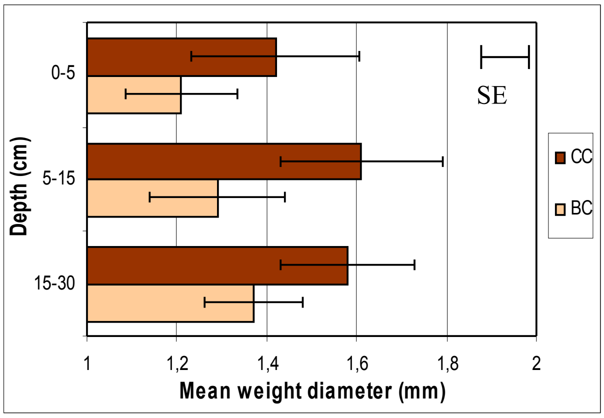

Figure 6. Rotation effects on aggregate mean weight diameter at multiple depth increments to 30 cm depth

Microaggregate stability

Microaggregate stability was characterized by means of rheology. Tillage and also rotation influenced the microaggregate stability (Table 4.), however, statistical analysis was not carried out, because the measurement was done only in two replications.

The absolute yield value is the shear stress, which is untolerable for the particle-particle network in microaggregates, so the bonds break down and the soil suspension starts to flow.

Table 4. Effect of tillage and rotation on microaggregate stability at multiple depth increments to 30 cm depth

Depth (cm)	Absolute Yield Value (Pa)			
	No-till		Plow	
	CC	BC	CC	BC
0-5	755	826	170	393
5-15	462	636	183	471
15-30	331	372	385	408

CC – corn monoculture BC – soybean-corn rotation

Comparing these results with the results for macroaggregate stability I have found, that, however macroaggregate stability similarly to microaggregate stability was higher in no-till compared to plow (Figure 7-8.), the effect of the different crop rotation systems was the opposite. Corn monoculture had higher macroaggregate stability, but lower microaggregate stability (Figures 9-10.) compared to the soybean-corn rotation.

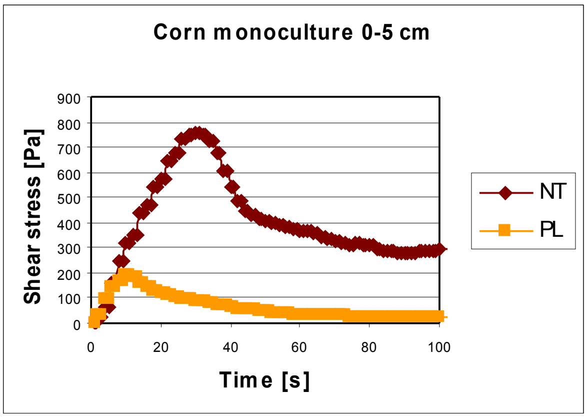

Figure 7. The effect of tillage on micro-aggregate stability at the 0-5 cm sampling depth in corn monoculture

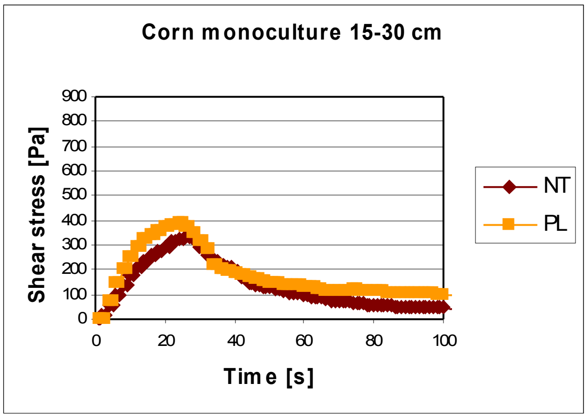

Figure 8. The effect of tillage on micro-aggregate stability at the 15-30 cm sampling depth in corn monoculture

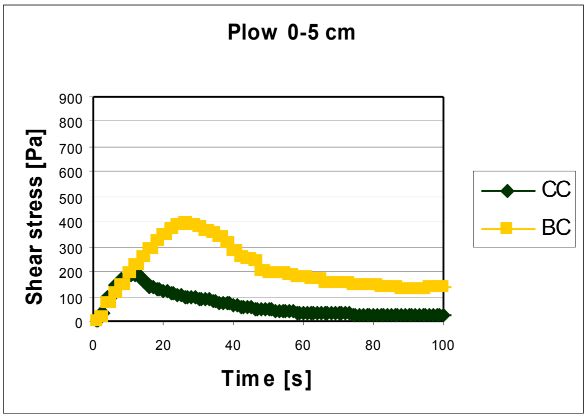

Figure 9. The effect of rotation on micro-aggregate stability at the 0-5 cm sampling depth in plow

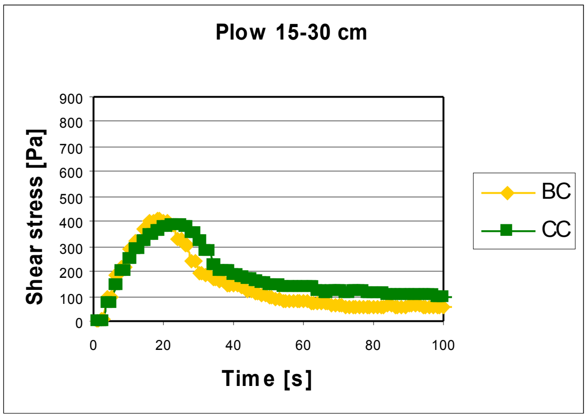

Figure 10. The effect of rotation on micro-aggregate stability at the 15-30 cm sampling depth in plow

WATER RETENTION

Water retention was influenced by tillage (Table 5.) but not by rotation; tillage × rotation interactions were not significant.

For volumetric water content, tillage treatment effects (Table 5.) were significant at α=0.01 at all depth increments at each measured pF value (pF 1.7, pF 2 és pF 2.5). The effect of tillage was less important on the gravimetric water content.

Table 5. Tillage system effects (averaged for two rotations) on volumetric water content at pF 1.7, pF 2 and pF 2.5 at multiple depth increments to 30 cm depth

Depth (cm)	Volumetric water content (cm^3/cm^3)		
	pF 1.7	pF 2	pF 2.5
	NT PL	NT PL	NT PL
0-5	41 ** 35	40 ** 33	38 ** 30
5-15	40 ** 34	39 ** 33	38 ** 32
15-30	38 ** 35	37 ** 34	36 ** 33

** Significant differences between two tillage systems at α=0.01

NT – no-till PL – moldboard plow

ELEMENTAL COMPOSITION OF HUMIC MATERIALS

The elemental composition of the humic acids was the following: carbon 35.3-46.0 %, hydrogen 4.5-5.9 %, nitrogen 3.7-5.3 % and oxygen 44.1-56.0 %. Fulvic acids contained 26.3-38.2 % carbon, 4.8-6.6 % hydrogen, 3.4-4.2 % nitrogen and 51.1-65.5 % oxygen. The C/N ratio ranged from 9.3 to 13.2 for humic acids and from 8.9 to 11.3 for fulvic acids. The H/C ratio ranged from 1.3 to 1.6 for humic acids and from 2.0 to 2.3 for fulvic acids, which suggests a trend for increased aromaticity of humic acids compared to fulvic acids.

The humic acid - fulvic acid ratio (HA/FA ratio) ranged from 1.21 to 0.43 and decreased with depth, demonstrating that the proportion of the humic acid fraction is decreasing but the proportion of the fulvic acid fraction is increasing with depth

The HA/FA ratio was higher for continuous corn than for the soybean-corn rotation; the HA/FA ratio was also higher for no-till than the plow system indicating a lower molecular size of soil organic colloidal fractions in these treatments.

MOLECULAR COMPOSITION OF HUMIC MATERIALS

The humic substances are very complex and heterogeneous molecules, therefore their FTIR spectrum is rather complex as well. The spectra are affected by overlapping peaks, which make their evaluation difficult. When we compare spectra among layers for the same treatments, we observe that spectra of no-till soils are more variable with depth than the spectra of the moldboard plow soils. Also more differences could usually be observed on spectra from the surface horizon (0-5 cm), than in the deeper 15-30, and 30-50 cm depths. Humic acid spectra also show more variability than fulvic acid spectra.

SUMMARY OF NEW SCIENTIFIC RESULTS

The new scientific results are the followings:

1. No-till resulted in a substantial gain of organic carbon and total nitrogen at the 0-30 cm depth interval, but in a reduction, relative to the plow system, in the 30-50 cm depth interval. These two tillage systems had similar soil organic carbon and total nitrogen concentrations at 50-100 cm depth.

2. When comparing the capacity of different tillage systems to sequester carbon, the assessments can be made more reliable, if organic carbon accumulation is measured to 1 m depth. Further, organic carbon and total nitrogen storage can be better evaluated in each sampling depth, if soil organic carbon and total nitrogen storage is reported not as concentrations (g/kg), but - considering the effect of potentially different bulk densities under different tillage systems – in mass per unit area (t/ha) or in equivalent soil mass (t/ha), which is corrigated by the different bulk densities.

3. Continuous corn stored slightly more organic carbon relative to soybean-corn rotation, but no substantial gain in organic carbon was observed with continuous corn despite the fact that total crop biomass returned to soil would have been at least 30% higher in continuous corn versus corn-soybean. The rather similar cumulative organic carbon results for the two rotations indicates residue mass may not be the most important factor in organic carbon retention by soil.

4. Comparing the effect of no-till, moldboard plowing and chisel plowing on the organic carbon content I concluded, that accumulation of soil organic carbon under these tillage systems decreases in the above mentioned order.

5. Based on the aggregate stability measurements I could draw the conclusion, that the residues of corn and soybean contribute to the formation of different kind of humic substances, so they perform different functions at different stages in the aggregate formation and conservation processes.

6. I have concluded, that at all examined depth increments in the 0-30 cm depth, at each measured point of the pF-curve, volumetric water content was higher with no-till compared to plowing. We could not verify the effect of rotation on water retention.

7. I could verify differences in the spectra of humic materials from different tillage and rotation systems and depth increments. I could measure differences in the humic acid/fulvic acid ratio of soil samples caused by the different rotations.

8. The 6-years no-till following 17 years of plowing resulted in the same amount of carbon stored in the soil, as the 24-years continuous no-till, which shows, that on this soil type, under the given conditions, differences in carbon storage between plowed and no-till soils after 17 years disappeared. This leads to the conclusion, that even 6 years in no-till are enough to increase carbon storage, when practicing conservation tillage.

RECOMMENDATIONS

RECOMMENDATIONS FOR PRACTICE

When we compare the effect of different tillage and rotation systems on soil carbon sequestration, it is very important, that we sample also the horizons below plowing depth, and we draw conclusions based on these results for that given area.

My results showed less difference in organic carbon storage between no-till and moldboard plow than between no-till and chisel plow, thus if periodic tillage must take place following no-till production for a number of years, I suggest moldboard plowing, which is favourable to sequester carbon than chisel plow. In addition, the substantially higher organic carbon storage of no-till over chisel should encourage more adoption of no-tillage, even if short-term. My results show, that periodic tillage of plots under no-till is not disadvantegous than continuous no-till concerning carbon sequestration. However, further sampling and investigation of different areas and soil types is needed to confirm these results before making recommendations.

Soil total nitrogen storage was higher with soybean-corn rotation, and in no-till. Based on these results, I recommend the use of lower nitrogen fertilizer rates in these treatments.

RECOMMENDATIONS FOR FURTHER RESEARCH

Tillage and rotation effects on organic carbon and total nitrogen storage are better evaluated if more information was available about the biomass produced underground. Rooting depth analysis under the depth of plowing contributes significantly to better evaluation in carbon storage. I recommend the investigation of soil pH effects on root growth, since low pH at particular depths in long-term no-till might partly explain why organic carbon mass decreases with depth parallel with decreasing pH in no-till, but not in the plow system.

The information gained from the spectra of humic substances is in many cases not definitive as the assignment of bands to particular groups is only tentative in complex mixtures of compounds. For this reason the results should be confirmed with other methods, e.g. solid-state ^{13}C nuclear magnetic resonance spectroscopy and by means of the E_4/E_6 ratio.

For better understanding the effects of different cropping systems on carbon storage, it is necessary to put more emphasis on the investigation of tillage and rotation effects on the different organic matter pools (active and passive) in the soil.

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