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Influence of wheel traffic and tillage on microbial biomass, residue decomposition and extractable nutrients in a Coastal Plain Soil[a]

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Abstract

The interactive effects of tillage and compaction from wheel traffic were tested on active bacterial and fungal biomass and organic matter decomposition in the planting row at the surface and within the plow layer of a Norfolk loamy sand (fine-loamy. siliceous, thermic Typic Kandiudult). This experiment was arranged in a split plot design with four replications. Main plots were compaction: 1) compaction from wheel traffic and 2) no compaction from wheel traffic; subplots were tillage system: 1) conventional tillage and 2) no-tillage. Despite asignificant increase in bulk density, compaction from wheel traffic and tillage system had no consistent effects on active bacterial or active fungal biomass either in the top 7.5 cm of soil or in the 15-20 cm depth of soil. Active bacteria and fungal biomass at both depths were usually lower in the winter months than the spring. summer or autumn months. Organic matter decomposition, nutrient mineralization and nutrient availability did not differ among soils that received tillage or compaction from wheel traffic. Organic matter decomposition was greater in all treatments when decomposition bags were buried at 15-20 cm than when they were placed on the surface of the soil. The soil that was sampled was an extremely sandy soil so there was probably not a significant effect of compaction on soil aeration and structure.

Introduction

Agricultural production systems throughout the south eastern United States include intensive tillage for seedbed preparation, incorporation of fertilization and weed control. Nutrients are retained to a greater degree in no-till and conservation tillage systems because soil organic matter and soil microorganisms are less disturbed than in plowed systems. No-till systems promote C accumulation at the soil surface due to lack of incorporation of crop residues. Wood and Edwards (1992) found that organic C and N were 67 and 66% higher, respectively, in the top 10 cm of soil when soybean, wheat and corn were grown under a no-till than a conventionally tilled system. Cambardella and Elliott (1994) found that as cultivation intensity increased from a bare fallow system to a no-till system the amount of soil organic matter, and the nitrogen enriched labile fraction of soil organic matter decreased. Nitrogen. P and K also accumulate at the soil surface due to deposition in crop residue. Wood et al. (1991) found that initiation of no-till resulted in higher soil organic carbon, soil organic nitrogen and less NO_3-N in the top 40 cm of soil. In the 40 to 180 cm depths less NO_3-N was found in the no-till system indicating that no-till farming may reduce NO_3 losses below the root zone. Availability of soil nutrients was greater under conservation tillage than under conventional tillage system (Edwards et al., 1992). Follett and Peterson (1988) and Hargrove (l985) reported that there was greater extractable Ca, Mg, P, Mg and Zn in the surface soils of no-till agronomic systems.

Intensive tillage usually leads to soil compaction from wheel traffic. Increasing size and weight of farm tractors is causing increasing compaction of soils throughout the United States. Wheel traffic from normal fanning operations compacted the soil to a depth

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of 45 cm and increased soil bulk density by as much as 400% (Liebig et al., 1993). Intensive tillage encourages rapid decomposition and depletion of soil organic matter, and has a negative long-term effect on soil structure resulting in slower water infiltration rates and reduced water holding capacity (Reeves et al., 1992). Nutrients are retained to a greater degree in no-till and conservation tillage systems because soil organic matter and soil microorganisms are less disturbed than in plowed systems. Soil compaction resulting from wheel traffic leads to decreased soil structure and porosity, decreased water content at field capacity, increased soil erosion and ultimately reduced yield and quality of crops by impeding root growth (Soane, 1990). Increases in soil organic matter may reduce compactibility by increasing resistance to soil deformation and/or by increasing soil elasticity. The objective of this project was to determine the interactive effects of tillage and compaction from wheel traffic on soil microorganisms and organic matter decomposition in a typical Coastal Plain soil.

Materials and methods

Site description

The study site soil is located at the E.V. Smith Research Center of the Alabama Agricultural Experiment Station near Shorter, Alabama, USA (32° 24.5'N, 85° 57'W). The soil is a Norfolk loamy sand (fine, loamy, siliceous, thermic Typic: Kandiudults). The soil is highly compactible and has a well developed hardpan at the 18-30 cm depth. Chemical and physical properties, cropping history and plant response to treatments are presented in Reeves et al. (1992). These treatments have been implemented since 1988.

Experimental design

This study was part of a continuing long-term project initiated in 1988 to determine the interactive effects of tillage method and soil compaction from wheel-traffic on crop yields, crop quality and soil properties. Tillage and soil compaction treatments initiated in 1988 were : 1) soil compaction from tractor traffic with conventional tillage, 2) no, compaction from tractor traffic with conventional tillage, 3) soil compaction from tractor traffic with no tillage and 4) no soil compaction from tractor traffic with no-tillage. Treatments were arranged as a split plot factorial design with four replications. In 1988 the area was subsoiled on 25-cm centers to a depth of 50-cm. Prior to 1990, all 16 plots received a fall disking to aid in cover crop establishment. Since 1990, the cover crop has been planted with standard no-till practices.

Field operations

The cropping system at the study site, upon which tillage and soil compaction treatments were imposed, was a soybean *(Glycine max* (L.) Merr) 'Delta and Pineland 105'-corn *(Zea mays* L.) 'Dekalb 689' rotation with crimson clover *(Trifolium incamatum* L.) as a winter cover crop. The study reported here was conducted during December 1993 to December 1994, to determine the impact of 6 years of compaction from wheel traffic and tillage system on soil microbial biomass, soybean stem decomposition, nutrient mineralization and nutrient availability. Corn was grown in 1993, followed by a winter crimson clover cover crop, with soybeans grown in the summer of 1994.

Field activities were carried out using an experimental wide-frame tractive vehicle (Monroe and Burt, 1989). The vehicle spans the 6.1 m wide research plots and performs field operations without applying traffic to the plots. A 4.6 Mg tractor was utilized to compact the soil on wheel-traffic treatments. During the fall the tractor was driven over the plots to simulate planting of the cover crop and any required fertilizer applications. The tractor was driven in trafficked plots in the spring/summer to imitate field preparations and planting that would be used by a grower employing four-row equipment.

Corn harvest occurred 28 October 1993. The cover crop was drilled on 2 November 1993. On 10 November 1993, 56 kg K ha^{-1}, 25 kg S ha^{-1} and 12 kg Mg ha^{-1} as 112 kg K_2S0_4-$2MgS0_4$ ha^{-1}) was applied to the site. In spring of 1994, the cover crop was sprayed with glyphosate, N (phosphonomethyl) glycine (0.46 kg ai ha^{-1}) and [2, 4-DB (2. 4-dichlorophenoxy) butyric acid] (0.027 kg ai ha^{-1}) 18 days prior to soybean planting, and sprayed again 11 days before planting with paraquat dichloride (l,l'-dimethyl-4, 4'-bypyridimium dichloride) (0.10 kg ai ha^{-1}) to ensure cover crop kill. Tillage in the conventional tillage treatment occurred on May 18 one day before soybean planting and wheel traffic were applied. The tillage operation involved two trips with a disk followed by one trip with a field cultivator. Soybean was planted 19 May 1994 in 75 cm rows at a seeding rate of 256,000 seeds ha^{-1}. Wheel-traffic was applied to com-

pact plots the same day to simulate events occurring in a grower's operation.

Sampling procedures

All measurements or samples were taken in row-centers, between soybean or crimson clover plants, Therefore no measurements were taken in soil that had been directly compacted by wheel traffic. Twelve random samples of soil for microbial testing were taken each month from the top 7.5 cm and from the 15-20 cm depth from each plot. Samples were taken in the middle week of each month. Samples were placed in plastic bags and transported to the laboratory, stored at 4°C and prepared for testing within 24 hours to not significantly alter microbial activity (West et al., 1986). We took nine samples of soil from each plot at the O-7.5 cm and nine samples at the 15-20 cm depth each month for microbial biomass estimation.

Immediately after harvest soybean stems were collected from field plots. Four grams of soybean stems were placed in each 13 x 13 cm, 1 mm mesh decomposition bag. Twenty decomposition bags were place on each plot; ten were placed on the surface and ten were buried 15-20 cm below the surface of the soil four weeks after harvest. Five decomposition bags were collected from the surface and 5 decomposition bags were collected from the 15-20 cm depth at 4, 8 and 12 months after placement.

Air temperature was measured hourly using a standard thermometer and soil moisture at 10 cm was measured gravimetrically in the middle week of eachmonth at the study site. Soil bulk density measurements at 3-8 cm depth were made using the core method described by Blake and Hartage (1986) on April 12, 1993. Soil bulk density measurements were not taken in the top 3 cm of soil due to large variations in residue distribution and differences in microrelief. Organic C and total N were determined on soil samples collected in May of 1994. Soil samples were dried at 55 °C for 48 hr and ground to pass a l-mm sieve. Soil C was analyzed using methods described in Nelson and Sommers (1982) and total N was analyzed using methods described in Keeney and Nelson (1982) on a LECO CHN-600 analyzer (LECO Corp., St. Joseph, MI). Plant material analyzed for total N and nutrients was oven-dried at 54 °C for 48 hr and ground to pass a 0.2 mm mesh sieve. Soil organic C and total N analysis were made with a LECO CHN-600 analyzer (LECO Corp., St. Joseph, MI).

Microbial biomass

Active bacterial and fungal biomass was estimated using methods described by Ingham and Klein (1984). A 1.000 g soil sample was diluted in 9.0 mL of 6 M phosphate buffer. One mL of and shaken at 120 rpm for 5 min. A 1.0 mL aliquot was removed and prepared for active fungal estimations by staining for *3* min with 1.0 mL of a 20 µg FDA to 1.0 mL water solution in 0.1 M phosphate buffer at pH 6.0. One mL of 1.5% agar in a pH 9.5, 0.1 M phosphate buffer was added to the FDA soil suspension, mixed well and an aliquot placed on a slide containing a known volume. Slides were examined by epifluorescent microscopy for FDA stained hyphal length at 100 x total magnification after preparation.

Active bacterial biomass was estimated using iodonitrotetrazolium (INT) stain for counting as described by Stamatiadis et al. (1990). A, 1.0 mL sample of initial soil suspension was diluted to a final dilution of 0.2 mg soil in 4 mL buffer. The soil suspension was incubated with 4 mL buffer for 60 min in the dark at 7O°C. Two slides per sample and 10 fields per slide were examined with epiflourescent microscopy for INT stained bacteria at approximately 1000 x magnification. Microbial observations were made with a Nikon Photomat I epiflourscent phase-contrast microscope. Phase objectives were adapted for epifluorscence with a mercury light source, an H2 filter module containing a wide band exciter filter at 390-470 nm, a dichromatic beam -splitter passing > 510 nm reflected light and a barrier filter restricting the light range to > 515 nm. We used an edge filter to narrow the excitation range to 455-490 nm in order reduce autofluorescensce interference.

Minimum and maximum hyphal diameters were measured in one field per slide, and the mean diameter was used to calculate fungal volume. Bacterial volume was computed from the number of soil bacteria per gram of soil. We assumed that bacterial spheres were 1 µm in diameter (Jenkinson and Ladd, 1981) and used a bacterial to biomass conversion factor of 120 µm C mm^{-3} for both bacteria and fungi, a 1.1 g cm^{-3} 3 wet density, a 0.33 dry matter content and a 0.41 carbon content in the bacterium or fungus (Jenkinson and Ladd, 1981).

Organic matter decomposition

On October 28, 1994, (immediately after harvest), soybean stems were collected from adjacent field plots.

We placed 4.00 grams of soybean stems in each 13 x 1.3 cm, 1 mm mesh decomposition bag. Thirty-six bags were placed on each plot on November 15, 1994 (three weeks after harvest). Nine bags were placed on the surface and nine bags were buried at depth of 15-20 cm. Three decomposition bags were collected from the surface and 5 decomposition bags from the 15-20 cm depth were recovered 4, 8 and 12 months from the time of placement. An oven dry equivalent weight for the soybean stems was calculated on 30 samples of soybean stems by drying at 80°C for 48 hours. Upon collection the soybean stems were dried at 8°C for 48 hours and weighed. Litter decomposition (k) was determined using the exponential decay model of Olson (1963).; $X/x = e^{-kt}$. Where x = initial weight of stems, X = weight of stems after time (t) in years.

Nutrient mineralization

Prior to placement and after 12 months of decomposition soybean stems were analyzed for nutrient content. Soybeans stems were treated as above then ground to pass a 1 mm mesh. A 1.0 gram subsample was ashed at 525°C in a muffle furnace for 4 hours. The ash was taken up in 10 mL of 6 M HCl brought to 50 cm^3 volume with distilled deionized water and analyzed for B, Ca, Cu, Fe, Mg, Mn, K, P, and Zn, with a Jarrall Ash 9000 inductively coupled plasma spectrometer (ICP). Total N was analyzed by a LECO CHN-600 nitrogen analyzer. Nutrients mineralized from soybean stems were calculated using the formula:

$$NM = N_{un} - [(1 - D) \times N_{dn}]$$

Where NM represents the amount of nutrients released due to soybean stem decomposition, N_{un}, is the concentration of nutrients in undecomposed soybean stems (micrograms nutrient per gram soybean stem), D is the percent soybean stem decomposition/ 100 and N_{dn} is the nutrient concentration in decomposed soybean stems (microgram nutrient per gram soybean stem (Entry et al., 1991)

Nutrient status of soil

The nutrient status of soil growing soybeans in 1994, was estimated using ion exchange resins (IER). Three weeks after harvest, five ion exchange resins were placed on each plot at the 15-20 cm depth. We had 20 IER bags placed on each treatment. Ion exchange resin bags were prepared by placing 20 mL (4.5 grams oven dry equivalent), of cation + anion exchange resin beads (J T Baker No. M 614 mixed-bead ion exchange resins) in nylonstockings (Binkley and Matson, 1983). Ion exchange resin bags were collected 1 year after placement. Resin beads were air dried and extracted for 24 hours in 40 mL 0.5 M KCl (Hart and Binkley, 1985). Ammonium and nitrate were analyzed using the Lachet nitrogen analyzer. A 10 mL subsample was analyzed for B, Ca, Cu, Fe, Mg, Mn, K, P, and Zn by inductively coupled plasma spectrometer (ICP).

Results

Air temperature was higher in the spring, summer and autumn than the winter while soil moisture was higher in the summer and winter than in spring and autumn (Fig. 1). Soil bulk density was higher in the treatments that received compaction from wheel traffic regardless of tillage method (Table 1). Soil C and total N in the 0-7.5 and 15-20 cm depths did not differ with compaction or tillage method. Active bacterial and fungal biomass in the top 7.5 cm of soil and at the 15-20 cm did not consistently differ among treatments throughout the year (Figs. 2 and 3). Active bacterial and fungal biomass in the top 7.5 cm and the 15-20 cm depth of soil was usually lower in the winter months than the spring, summer of autumn months. After 4, 8 and 12 months of decomposition rates of soybean stems at the top soil surface and at the 15-20 cm did not differ among the tillage and compaction from wheel traffic treatments (Fig. 4). Nitrogen, P, K, Ca, Mg, B and Zn mineralization from soybean stems after 12 months of decomposition at the soil surface and at the 15-20 cm did not differ among the tillage and compaction from wheel traffic treatments (Tables 2 and 3). The conventional tillage x compaction from wheel traffic treatment mineralized more Fe and Mn than both no-till treatments. Nitrogen, P, K, Ca, M, Mn, Fe, B and Zn extracted from cation/anion exchange resins after 12 months did not differ among the tillage and compaction from wheel traffic treatments (Table 4).

Discussion

We found that after 6 years of implementation, tillage and compaction due to wheel traffic had no consistent effects on active bacterial and active fungal biomass. organic matter decomposition, nutrient mineralization and nutrient availability. Our results disagreed with

Table 1. Influence of compaction from wheel traffic and tillage on soil bulk density, soil organic carbon and organic nitrogen

Treatment	Bulk density at 3–8 (g cm^3) cm depth	Organic carbon (g element kg^{-1} soil) 0–7.5cm	Organic carbon (g element kg^{-1} soil) 15–20cm	Organic nitrogen (g element kg^{-1} soil) 0–7.5cm	Organic nitrogen (g element kg^{-1} soil) 15–20cm
Conventional tillage with no traffic	1.32 b[z]	5.05 a	3.47 a	0.57 a	0.47 a
Conventional tillage with traffic	1.61 a	5.03 a	3.22 a	0.63 a	0.47 a
No tillage with no traffic	1.36 b	4.75 a	3.33 a	0.58 a	0.43 a
No tillage with traffic	1.62 a	5.05 a	3.77 a	0.60 a	0.47 a

[z]In each column, values followed by the same letter are not significantly different as determined by the Least Square Means Test ($p \leq 0.05$).

Table 2. Nutrients mineralized from soybean stems after 12 months of decomposition on the soil surface

Treatment	N	P	K	Ca	Mg	Mn	Fe	B	Zn
	(μg nutrient)								
Conventional tillage with no traffic	1.4 a[y]	-65.2 a[z]	-118.6 a	- 650.2 a	381.7 a	-121.9 a	-1304.3 a	21.7 a	- 6.1 a
Conventional tillage with traffic	1.2 a	-10.7 a	- 76.0 a	- 571.9 a	343.7 a	-103.9 ab	- 967.6 ab	22.3 a	- 4.5 a
No tillage with no traffic	1.3 a	5.2 a	- 77.9 a	- 592.9 a	341.4 a	- 75.0 b	- 553.0 b	21.1 a	-15.6 a
No tillage with traffic	1.2 a	9.6 a	- 45.1 a	-1194.5 a	304.5 a	- 66.3 b	- 624.0 b	17.8 a	4.0 a

[z]Means of nutrients absorbed by organic matter.
[y]In each column values followed by the same means are not significantly different as determined by the Least Square Means Test ($p \leq 0.05$).

results from other studies. Doran (1980), Linn and Doran (1984), Buchanan and King (1992) and Angers et al. (1993) found that microbial biomass was significantly higher in the surface of no-till than in conventionally tilled soils. Microbial biomass in these plots was usually but not always lower than microbial biomass reported in Doran (1980), Linn and Doran (1984), Buchanan and King (1992) and Angers et al. (1993). There are most likely two main reason for the differences between this study and others. First, this study was implemented in sandy soils with low clay contents while Doran (1980), Linn and Doran (1984), Buchanan and King (1992) and Angers et al. (1993) implemented their studies in soils that had appreciably less sand and substantially more clay. Therefore, compaction from wheel traffic is expected to have a much greater affect on soil porosity, aeration and water movement and thus on soil microbial processes in the cited studies than in this study (Dick et al., 1988; Soane, 1990). Although, we found a significant increase in bulk density, water movement and aeration in this soil was probably not affected to the degree that it was in Doran (1980), Linn and Doran (1984), Buchanan and King (1992) and Angers et al. (1993). The second reason is that Doran (1980), Linn and Doran (1984), Buchanan and King (1992) and

Table 3. Nutrients mineralized from soybean stems after 12 months of decomposition at 15–20 cm depth[z]

Treatment	N	P	K	Ca	Mg	Mn	Fe	B	Zn
	(μg element)								
Conventional tillage with no traffic	1.4 a[y]	91.1. a	33.8 a	318.2 a	634.4 a	-49.2 a	-243.3 a	29.0 a	- 3.7 a
Conventional tillage with traffic	1.3 a	24.2a	-69.6 a	92.7 a	597.9 a	-73.6 a	-599.2 a	28.0 a	- 8.2 a
No tillage with no traffic	1.4 a	138.0 a	20.2 a	358.9 a	685.9 a	-25.5 a	-145.8 a	29.8 a	4.0 a
No tillage with traffic	1.4 a	138.9 a	80.7 a	677.3 a	732 a	-47.9 a	-232.7 a	27.9 a	4.3 a

[z]Means of nutrients absorbed by organic matter.
[y]In each column values followed by the same means are not significantly different as determined by the Least Square Means Test ($p \leq 0.05$).

Table 4. Nutrients extracted from ion exchange resins in soil after seven years of tillage and compaction

Treatment	NH_4-N	NO_3-N	P	K	Ca	Mg	Mn	Fe	Mo	Zn
	(μg element)									
Conventional tillage with no traffic	5.9 a[z]	481 a	7.1 a	52,308 a	421 a	302 a	3.3 a	0 a	0.8 a	1.6 a
Conventional tillage with traffic	6.2 a	467 a	4.2 a	48,646 a	364 a	263 a	2.21 a	0 a	2.7 a	1.3 a
No tillage with no traffic	5.3 a	457 a	9.9 a	52,234 a	424 a	275 a	2.25 a	0 a	0.6 a	3.5 a
No tillage with traffic	4.8 a	482 a	6.5 a	50,236 a	428 a	307 a	1.33 a	0 a	0.5 a	1.4 a

[z] In each column, values followed by the same letter are not significantly different as determined by the least square means test ($p \leq 0.05$)

Angers et al. (1993) implemented their studies in more northerly climates where organic matter degradation is slower (Meetenmyer, 1978). Air temperatures. rainfall and soil moisture indicates that Alabama's climate is warmer and more mesic than in areas where other no-till studies were implemented. Organic matter decomposition proceeds rapidly in this soil due to low concentration of lignin in crop residues, the high amount of nitrogen from decomposing crimson clover and the warm moist soil conditions found in central Alabama soils (Enriquez et al., 1993; McClaugherty et al., 1985; Melillo et al., 1982; Tayloret al.. 1989). Organic matter decomposition in this study was more rapid than reported in similar studies (Beare, 1992; Holland and Coleman, 1987). Buildup of soil organic matter in semi-tropical soil from reduced tillage would seem to require longer time periods than in the more northerly climates where organic matter decomposition proceed more slowly (Meentemyer, 1978). The pattern of organic matter decomposition agreed with those of others. Beare (1992) and Holland and Coleman (1981) found that surface litter decomposed more rapidly in no-till systems than conventionally tilled systems and surface litter in both conventionally tilled and no-till

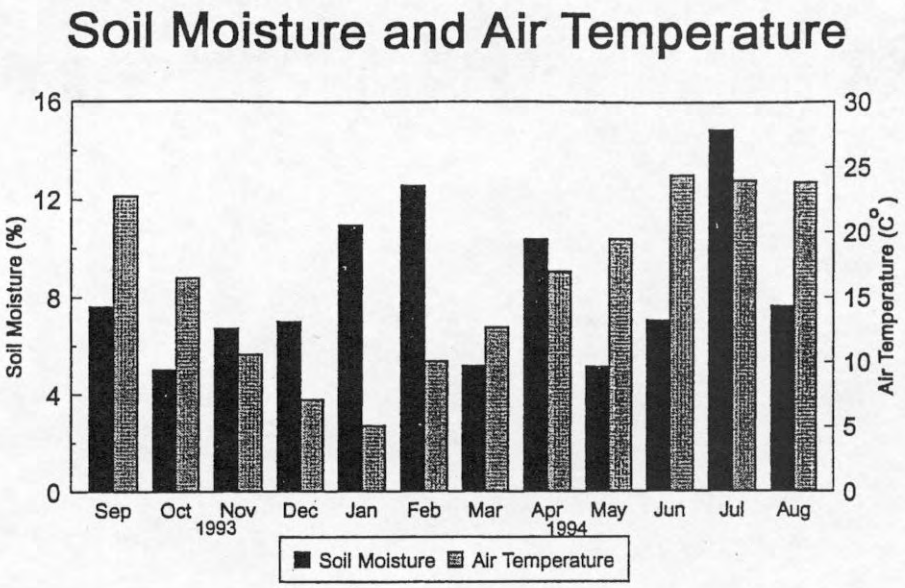

Figure 1. Mean air temperature and soil moisture at 10 cm depth taken at the E V Smith Agricultural Research Station from September 1993 to August 1994.

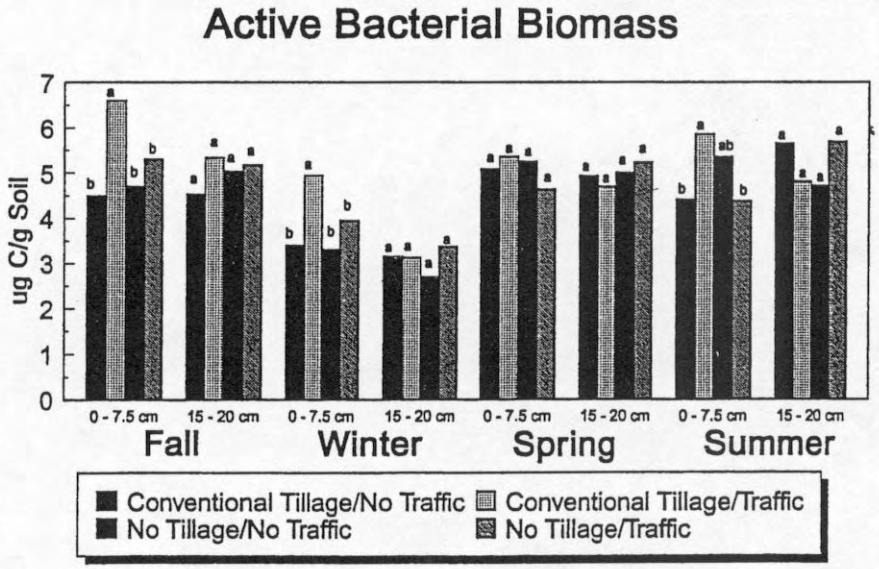

Figure 2. Active bacterial biomass in the top 7.5 cm and at 15 –20 cm depth of soil as affected by compaction from wheel traffic and tillage. * In each season, in each depth, values followed by the same letter are not significantly different as determined by the Least Square Means test ($p \leq 0.05$).

agroecosystems decomposed more slowly than when litter was buried.

There were no effects of compaction due to wheel traffic on active bacterial and fungal biomass despite the significant effect on soil bulk density. In soils containing higher concentrations of silt and clay soil compaction should substantially reduce soil aeration and structure. These treatments have been in place since 1988. Differences in soil physical and chemical properties have been well documented (Reeves et al., 1992). so differences in microbial activity C and N concentration, organic matter decomposition and nutrient mineralization are expected to be evident in the future.

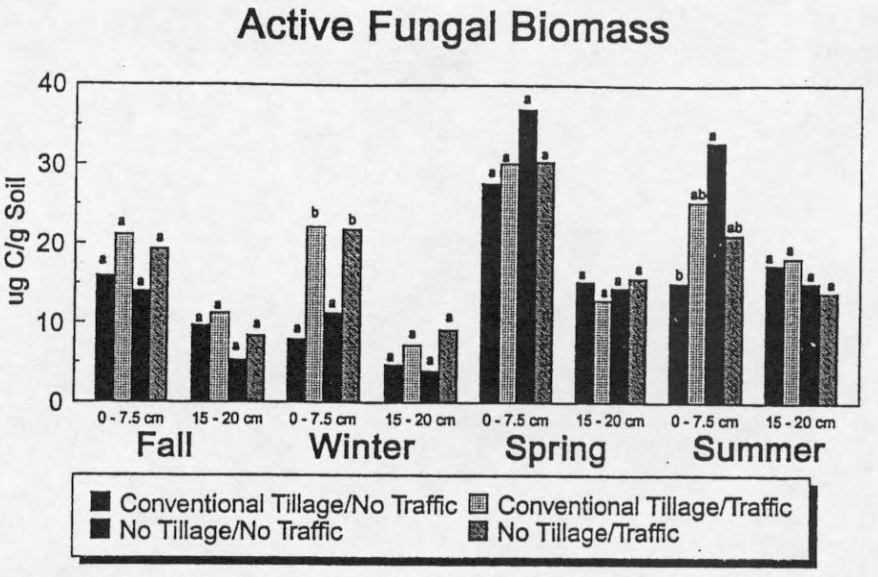

Figure 3. Active fungal biomass in the top 7.5 cm and at 15–20 cm depth of soil as affected by compaction from wheel traffic and tillage. * In each season, in each depth, values followed by the same letter are not significantly different as determined by the Least Square Means test ($p \leq 0.05$).

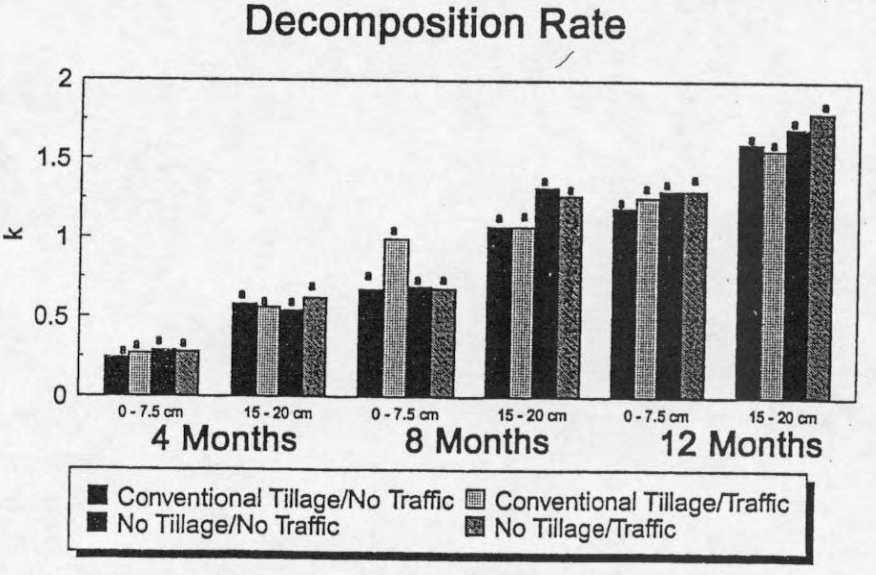

Figure 4. Decomposition rate (k) of soybean stems on the surface and 15–20 cm deep (plow layer) in soils affected by compaction from wheel traffic and tillage. * In each time period (4, 8 or 12 months), in each depth, values followed by the same letter are not significantly different as determined by the Least Square Means test ($p \leq 0.05$).

References

Angers D A, N'dayegamiye N and Cote D 1993 Tillage induced differences in organic matter of particle size fractions and microbial biomass. Soil Sci. Soc. Am. J. 57, 512–516.

Beare M H, Parmelee R W, Hendrix P and Cheng W 1992 Microbial and faunal interactions and effects on litter nitrogen and decomposition in agroecosystems. Ecol. Monogr. 62, 569–591.

Binkley D and Matson P 1983 Ion exchange resin bag method for assessing soil nitrogen availability. Soil. Sci. Soc. Am. J. 47, 1050–1052.

Blake G R and Hartage K H 1986 Bulk density. *In* Methods of Soil Analysis Part 1. Ed. A Klute. pp 364–366. American Society of Agronomy, Madison, WI, USA.

Buchanan M and King L D 1992 Seasonal fluctuations in soil microbial biomass carbon, phosphorus and activity in no-till and

reduced-chemical-input maize agroecosystems. Biol. Fertil Soils 13, 211–217.

Cambardella C A and Elliott E T 1994 Carbon and nitrogen dynamics of soil organic matter fractions from cultivated grassland soils. Soil Sci. Soc. Am. J. 58, 123–130.

Dick R P, Myrold D D and Kerle E A 1988 Microbial biomass and soil enzyme activities in compacted and rehabilitated skid trail soils. Soil Sci. Soc. Am. J. 52, 512–516.

Doran J W 1980 Soil microbial and biochemical changes associated with reduced tillage. Soil Sci. Soc. Am. J. 44, 765–771.

Edwards J H, Thurlow D L and Easton J T 1992 Influence of tillage and crop rotation on yields of corn, soybean and wheat. Agron. J. 80, 76–80.

Enriquez S, Duarte C M and Sand-Jensen K 1993 Patterns in decomposition rates among photosynthetic organisms: the importance of detritus C:N:P content. Oecologia 94, 457–471.

Entry J A, Rose C L and Cromack K Jr 1991 Litter decomposition and nutrient release in ectomycorrhizal mat soils of a Douglas-fir ecosystem. Soil Biol. Biochem. 23, 285– 290.

Follett R F and Peterson G A 1988 Surface soil nutrient distribution as affected by wheat fallow tillage systems. Soil Sci. Soc. Am. J. 52, 141–147.

Hart S C and Binkley D 1985 Correlations among indices of forest soil nutrient availability and fertilized and unfertilized loblolly pine plantations. Plant and Soil 85, 11–21.

Hargrove W L 1985 Influence of tillage on nutrient uptake and yield of corn. Agron. J. 77, 763–768.

Holland E A and Coleman D C 1987 Litter placement effects on microbial and organic matter dynamics in an agroecosystem. Ecology 68, 425–433.

Ingham E R and Klein D A 1984 Soil fungi relationships between hyphal activity and staining with fluorescein diacetate. Soil Biol. Biochem. 16, 273–278.

Jenkinson D S and Ladd J N 1981 Microbial biomass in soil: measurement and turnover. *In* Soil Biochemistry, Vol 5. Eds. E A Paul and J N Ladd. pp 465–471. Marcel–Decker, New York, USA.

Keeney D R and Nelson D W 1982 Nitrogen inorganic forms. *In* Methods of Soil Analysis, Part 2. Chemical and microbiological Properties Eds. A L Page, R H Miller and D R Keeney. pp 643–693. American Society of Agronomy, Madison, WI, USA.

Leibeig A, Jones A J, Mielke L N and Doran J W 1993 Controlled wheel traffic effects on soil properties in ridge tillage. Soil Sci. Soc. Am. J. 57, 1061–1066.

Linn D M and Doran J W 1984 Aerobic and anaerobic microbial populations in no-till and plowed soils. Soil Sci. Soc. Am. J. 48, 794–799.

McClaugherty C A, Pastor J, Aber J D and Melillo J M 1985 Forest litter decomposition in relation to soil nitrogen dynamics and litter quality. Ecology 66, 266–275.

Meentemyer V 1978 Macroclimate and lignin control of litter decomposition rates. Ecology 59, 465–472.

Melillo J M, Aber J and Muratore J F 1982 Nitrogen and lignin control of hardwood leaf litter decomposition dynamics. Ecology 63, 621–626.

Monroe G E and Burt E C 1989 Wide frame tractive vechile for controlled-traffic research. Appl. Eng. Agric. 5, 40–43.

Nelson D W and Sommers L E 1982 Total carbon, organic carbon and or anic matter. *In* Methods of Soil Analysis Part 2. Chemical and microbiological Properties. Eds. A L Page, R H Miller and D R Keeney. pp 539–577. American Society of Agronomy, Madison, WI, USA.

Olson J S 1963 Energy storage and the balance of producers and consumers in ecological systems. Ecology 59, 322–331.

Reeves D W, Rogers H H, Droppers J A, Prior S A and Powell J B 1992 Wheel-traffic effects on corn as influenced by tillage system. Soil Tillage Res. 23, 177– 192.

Soane B D 1990 The role of organic matter in soil compactability: a review of some practical aspects. Soil Tillage Res. 16, 179–201.

Stamatiadis S, Doran J W and Ingham E R 1990 Use of staining inhibitors to separate fungal and bacterial activity in soil. Soil Biol. Biochem. 22, 81–88.

Taylor B T, Parkinson D and Parsons W J F 1989 Nitrogen and lignin content as predictors of litter decay rate: a microcosm test. Ecology 70, 97–104.

Tobert H A and Wood C W 1992 Effects of soil compaction and water-filled pore space on soil microbial activity and N losses. Commun. Soil Sci. Plant Anal. 23, 1321–1331.

Voorhees W B and Lindstrom M J 1984 Long term effects of tillage method on soil tilth independent of wheel traffic. Soil Sci. Soc. Am. J. 48, 152–156.

West A W, Ross D J and Cowlin J C 1986 Changes in microbial C, N, P, and ATP contents, numbers and respiration on storage of soil. Soil Biol. Biochem. 18, 141–148

Wood C W and Edwards J H 1992 Agroecosystem management effects on soil carbon and nitrogen. Agric. Ecosys. Environ. 39, 123–138.

Wood C W, Westfall D G, Peterson G A and Burke I C 1990 Impacts of cropping intensity on carbon and nitrogen mineralization under no-till dryland agroecosystems. Agron. J. 82, 1115–1120.

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