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Rainfall and tillage effects on soil structure after alfalfa conversion to maize on a clay loam soil in New York

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Abstract

Soil degradation is accelerated when perennial crops are converted to annual row crops, primarily due to increased soil disturbance from tillage. Subsequent heavy rainfall may induce soil settling, reduce macroporosity and increase hardsetting upon drying. An experiment involving plow and no-tillage and two simulated rainfall treatments ('wet' and 'dry') was conducted on Kingsbury clay loam soil in northern New York in 1992 and 1993 to study their effects on soil structure under maize (*Zea mays* L.) after conversion from alfalfa (*Medicago sativa* L.), and to evaluate the use of spectral analysis of micropenetrometer observations for studying soil aggregation. Undisturbed soil cores were collected from the row and trafficked and non-trafficked interrow positions at the 0.05 and 0.15 m depths and used for laboratory measurement of soil strength and pore system properties. These well-structured soils show a high contribution (up to $0.15\,\mathrm{m^3\,m^{-3}}$) of macropores to the total porosity of the soil. Soil strength was generally slightly higher for no-till (NT) than plow till (PT), although only significant in 1992. Soil strength in the surface layer did not change significantly with drying. Spectral density patterns did not show strong treatment effects, although distinct peaks reflect 3.0–3.5 mm stable structural units within macroaggregates. Simulated rainfall treatments and tillage treatments generally did not strongly affect measured soil properties, presumably due to stable soil structure. Structurally stable clay loam soils show little effect of tillage or settling on soil physical properties in the first years after alfalfa to maize conversion, and have good potential for long-term annual crop production if properly managed.

Keywords: Soil structure; Tillage; Soil settling; Spectral analysis; Crop rotation; New York

1. Introduction

Soil structure and aggregation are strongly influenced by processes such as tillage, cropping system, and climate (Guérif et al., 2001). Perennial crops generally improve soil structure, while annual row cropping often results in structural degradation, mainly as a result of a loss of ground cover and organic matter losses from soil disturbance (Magdoff and van Es, 2000). No-tillage systems under annual row cropping, however, reduce such structural degradation, or may reverse it, compared to conventional tillage systems, and after several years generally show higher aggregate stability, soil stabilizing compounds such as glomalin (Wright et al., 1999; Gomez et al., 2001), and infiltrability (McGarry et al., 2000).

Conventional tillage increases the volume of larger pores (at least for the short-term), but the continuity of macropores may be destroyed (Hill, 1990). Under no-till (NT), total porosity is usually smaller than conventional till, but pore systems are more continuous because worm and root channels and vertical cracks

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between peds are not disturbed (Cassel, 1985; Unger and Fulton, 1990). The altered pore size distribution brought about by tillage is very unstable and tends to change as the season progresses (Mapa et al., 1986). By loosening the soil, conventional tillage forms more macropores at the beginning of the season, but the persistence of this alteration depends largely on the structural stability of the soil, the rainfall patterns that may occur after tillage, and the occurrence and timing of field traffic.

In the period immediately following tillage, lower strengths (penetration resistance) are generally measured for tilled than no-tilled soils as tillage loosens the soil (e.g. Cox et al., 1990; Horne et al., 1992), which is often an incentive for farmers to use tillage when soils have already become degraded (Magdoff and van Es, 2000). However, some research efforts show minimal tillage effects on soil strength (e.g. Mielke et al., 1984; Simmons and Cassel, 1989; Hermawan and Cameron, 1993), which is often the case for structurally unstable soils that settle due to post-tillage rainfall.

Soil water content is an important soil property determining the effect of tillage on soil structure. Soils are generally most friable when tilled at or slightly below the lower plastic limit (Ojeniyi and Dexter, 1984; Dexter and Bird, 2001). With increasing water content the friability decreases, but deformation occurs. The dispersibility of clay increases with water content during tillage, once it exceeds a critical minimum (Kay, 1990). The process of repeated wetting and drying increases the variability in tensile strength and porosity in the soil, creates failure zones, and results in a progressive decrease in aggregate strength (Dexter et al., 1984) and size (Shiel et al., 1988). Larger aggregates have a greater number of failure zones with low strength and therefore are more susceptible to wetting- and drying-induced structural changes.

Difficulties are experienced in quantifying tillage-induced changes in soil because of temporal and spatial variability. Cassel (1985) reported a decrease of mean surface soil strength from 0.27 kPa at tillage to 0.15 kPa 2 weeks after that, and 0.75 kPa a month later, which coincided with the increase of water content from 0.042 to 0.081 and subsequent decrease to 0.036 $\mathrm{Mg\,m^{-3}}$. An increase in saturated hydraulic conductivity after tillage, and subsequent 100-fold decrease was measured by Mapa et al. (1986), which was attributed to changes in pore size distribution due to soil settling subsequent to tillage. Up to a 300% increase in macroporosity after plowing and subsequent decrease upon soil settling was measured by van Es (1993).

Studies on soil degradation are hindered by the difficulty to directly measure soil structure. Spectral analysis of micropenetrometer measurements (Grant et al., 1985; Hadas and Shmulewich, 1990) can provide valuable information on aggregate size distribution and the presence of weaker zones or pores. In this approach, intensively measured penetrometer measurements are transferred from space–domain observations to functions of frequency (Jenkins and Watts, 1968; Rayner, 1971). The presence of peaks in the spectral density pattern results from cyclic observations at a specified frequency or wavelength (Roseberg and McCoy, 1988). Soil voids and clod centers result in periodic small and large soil strength values, respectively, and peaks in their spectral density pattern (Hadas and Wolf, 1987). By comparing variance spectra of several aggregates sizes, Grant et al. (1985) concluded that larger soil aggregates are made up of smaller component aggregates, and the larger ones are more resistant to penetration. Hadas and Shmulewich (1990) assessed the use of spectral analysis as a practical method for determining soil structural spatial arrangement, and reported distinct periodic variations in structural arrangement in a freshly plowed soil that conformed to dimensions and positioning of clods. The objectives of this research were to determine the effects of tillage and rainfall on soil structural indicators under maize after conversion from alfalfa, and to evaluate the use of spectral analysis as a method for studying changes in soil structure in a fine-textured clay loam soil.

2. Materials and methods

2.1. Site and treatments

This study was conducted in 1992 and 1993 at the Cornell University Experimental Farm in Willsboro, NY (44.22°N, 73.26°W). The soil is a Kingsbury clay loam (Gleyic Luvisol, FAO; fine, illitic, mesic, Aeric Ochraqualf, USDA) originated from glacio-lucustrine deposits, and has an argillic horizon with 400 $\mathrm{g\,kg^{-1}}$ clay. Drainage at the experimental site has been improved with subsurface tile drains installed at 0.91 m depth and 18.3 m spacing. The site was under alfalfa sod for 5 years prior to this experiment.

Two tillage treatments, plow till (PT) and NT were applied in $27.5 \times 18.3\,\mathrm{m}^2$ plots in a spatially balanced randomized complete block design (van Es and van Es, 1993) with four replicates. Alfalfa was chemically killed with glyphosate in the fall of 1991, and moldboard plowing was performed to a depth of 0.20 m in PT plots using a four-bottom moldboard plow on 21 May 1992 and 25 May 1993. Soil water levels were well below the plastic limit in the dry spring of 1992. In the wetter spring of 1993, the top 10 cm of soil was generally above and the bottom half of the plow layer was generally below the plastic limit. Secondary tillage was performed on the same dates with an offset double disk. Plots were disked a second time on the following day in 1993 to ameliorate cloddy seedbed conditions. Maize (cv. Pioneer 3751, GDD rating 1900) was planted on all plots at 0.76 m row spacing with a four-row Buffalo planter (Fleischer Manufacturing Co., Lincoln, NE). Fertilizer and herbicide applications were based on standard recommendations (Cornell Cooperative Extension, 1991). No nutrient deficiencies or pest pressures were observed during the course of the experiment. Planting and harvesting was performed with four-row equipment using controlled traffic.

Soon after planting, microplots were established by pressing metal rings of 1 m diameter and 0.45 m height into the soil to a depth of 0.25 m using a backhoe. They were placed to include row, non-trafficked interrow and trafficked interrow positions. Four microplots were established inside each of two tillage plot replicates, two pairs at 8 m from the tillage plot borders. Rings were usually kept uncovered to allow for normal crop development, but were covered with plastic sheets during natural rain events. Three custom-made tensiometers were installed in the non-trafficked interrow position in each microplot at the 0.05, 0.10 and 0.25 m depth.

A custom-made rainfall simulator of $1.1\,\mathrm{m}\ W \times 1.1\,\mathrm{m}\ L \times 0.25\,\mathrm{m}\ H$ was used to impose two simulated rainfall treatments, wet and dry, to soil in the microplots. The rainfall simulator was based on the design by Ogden et al. (1997) and included coiled capillary tubes (0.76 mm ID) of 0.10 m length to create simulated rain drops. A Marriot-type air-entry tube controlled the rate of water application at $25\,\mathrm{mm\,h^{-1}}$. In the wet rainfall regime, soil water potential at 0.10 m depth was allowed to reach −30 kPa, after which simulated rainfall was applied to bring the soil to saturated condition ($\psi = 0$ kPa), which theoretically favors aggregate breakdown and settling. In the dry regime soil water potential at the same depth was brought to −6 kPa once the soil had dried to −60 kPa. In each pair of microplots, one was used for the wet rainfall regime, while the other was used for the dry regime. Amounts of simulated rainfall applied to each treatment are shown in Table 1.

2.2. Measurements

Intact soil cores, 75 mm diameter and 75 mm height, were collected within microplots at 9, 19, 33 and 46 days after tillage (DAT) in 1992 and 8, 35, 66 and 81 DAT in 1993. One half of each microplot was used for a single sampling event. A custom-made core sampler was driven into the soil using a hydraulic probe

Table 1
Amounts and dates for simulated rainfall (mm) applied on microplots in 1992 and 1993

Year	DAT	Tillage (rainfall) treatment			
		PT (high rate)	PT (low rate)	No till (high rate)	No till (low rate)
1992	16	65	–	35	–
	29	65	–	30	–
	31	–	38	–	24
	42/43	56	20	18	20
1993	30/31	41	37	33	–
	33	–	–	–	34
	45	35	33	24	26
	69	16	–	10	–

(Giddings, Fort Collins, CO). It allowed for simultaneous sampling of two soil cores centered at 0.05 and 0.15 m depths. Replicate samples were collected from both depths from the row, non-trafficked interrow and trafficked interrow. Samples were stored at 2 °C until further analysis.

Soil cores removed from storage were kept at room temperature for ~2 h, and subsequently saturated by wetting from the bottom over a 5–7-day period. The volume fraction of pores greater than 0.79 mm ($\psi = 0.37$ kPa) was determined by allowing free drainage of soil cores on saturated cheese cloth. Soil water retention at −1.62, −2.87, −5.37, −10.37, −20.37 and −40.37 kPa matric potentials was determined using custom-made water retention apparatus with 0.42 μm nylon filter membranes. Bulk density was determined on each core after determining oven-dry weight.

Another set of undisturbed soil cores was transferred, after saturation, to water retention apparatus described previously and equilibrated to the −5, −10, −30, −60 and −100 kPa potential level, with an equilibration time of 6 days. For each of the 80 cores (five soil water potential levels for two replicates of each of two rainfall regimes for two replicates of each of two tillage treatments), soil strength was measured using automated micropenetrometer apparatus. The micropenetrometer consisted of a 30° angle cone of 2 mm base soldered to a 1.4 mm diameter and 14 mm long stainless steel tube. An analog button load cell (Omega Engineering Co., Stamford, CT) encased in a brass capsule was connected to the probe, which was hooked up to an automated data acquisition system (model DASCON, Omega Engineering Co., Stamford, CT) installed in a PC. Software supplied by the manufacturer was used with modifications. The equilibrated soil cores were placed on the moving plate of a compression test machine (10,000 kg stepless Wykeham Farrance, Slough, UK) which allowed for penetration at a rate of 0.67 mm s^{-1}. The data acquisition system recorded penetration resistance once in every second so that 900 data points were recorded over a distance of 600 mm for each soil core. The depth of penetration (mm) and soil strength (MPa) were saved in an ASCII file for each core. Data from the upper 10 mm (150 data values) were discarded prior to the analysis to remove edge effects.

2.3. Statistical analysis

Statistical analyses of soil strength (averaged over all data points of each core) and soil water retention data were performed as repeated measures analysis of variance using the SAS GLM procedure (SAS, 1985). Data from two rainfall treatments were pooled within each tillage treatment, since rainfall treatments did not result in significant effects and the experiment was minimally replicated.

Finite Fourier transformation was used to decompose the micropenetrometer data series into a sum of sine and cosine waves of different amplitudes and wavelengths (Rayner, 1971). The Fourier transform decomposition of the series Y_x is

$$Y_x = \frac{a_0}{2} + \sum_{k=1}^{m} [a_k \cos(\omega_k x) + b_k \sin(\omega_k x)] \qquad (1)$$

where Y_x are data values, x is the distance expressed as consecutive measurements ($x = 1, 2, \ldots, n$), m the number of frequencies in the Fourier decomposition ($m = n/2$ if n is even; $m = (n-1)/2$ if n is odd), a_0 the mean term, k the number subscript of a set of sine and cosine wave functions ($k = 1, 2, \ldots, m$, where m is the number of sets of sine and cosine functions), a_k the cosine coefficients, b_k the sine coefficients and ω_k the Fourier frequencies ($\omega_k = 2\pi k/n$).

The spectral densities were calculated using the relationship (Hadas and Shmulewich, 1990)

$$R_f = \frac{1}{\pi}\left(1 + 2\sum_{k=1}^{m} r_k W_k \cos\left\{\frac{fk}{L}\right\}\right) \qquad (2)$$

where R_f are spectral densities, r_k are autocorrelations for lag k, W_k smoothing function such as Bartlett's spectral window or Tukey's spectral window (Jenkins and Watts, 1968), f the frequency, k the number of separation intervals and L the number of steps by which f was incremented.

Spectral analysis of the micropenetrometer data was performed using the SAS SPECTRA procedure (SAS, 1993). Only penetrometer data obtained at the −100 kPa soil water potential level were used for spectral analysis, as treatment effects become more prominent as the soil dries. Spectral densities estimated by this analysis were tested against white noise by Bartlett's Kolmogorov–Smirnov statistics (Bartlett, 1966). Spectral densities were plotted against wavelength to obtain a picture of the periodicity of soil strengths within the cores. Only the parts with major frequencies were plotted to maintain clarity. Spectral densities from two rainfall treatments were pooled within each tillage treatment, as they did not result in significant effects and the experiment was minimally replicated.

3. Results and discussion

3.1. Bulk density, water retention and pore size distribution

Bulk density and soil water retention are primarily affected by textural effects, but soil structure can introduce variations in the larger pore ranges (Bache et al., 1981). Minimal effects of the tillage and rainfall treatments were measured for bulk density (Table 2). No consistent differences in water retention properties were observed between tillage treatments for either depth in 1992 and 1993 (Karunatilake, 1996; data not shown).

Macroporosity and pore continuity are important indicators of the effects of tillage on soil structure (Ball and O'Sullivan, 1982). Linear models for water retention curves are often inappropriate for clay soils, because of lack of gradation in pore sizes, i.e., presence of both large structure-induced pores and small texture-related pores with few of intermediate size (Bache et al., 1981). Analysis of the effects of tillage, rainfall, and time on the two largest pore size classes (radii >386 μm and radii between 102 and 386 μm) for the non-trafficked interrow position shows minimal effect from any of these potential sources of variability for the non-trafficked interrow position (Table 3). Measurements in non-trafficked interrow position yielded similar trends for the row and trafficked interrow positions (Karunatilake, 1996). A lack of tillage effects on pore size distribution was also reported by Francis and Knight (1993) and Cassel et al. (1995).

3.2. Tillage and rainfall effects on soil strength

Soil strength measured as penetration resistance provides a sensitive measure of soil heterogeneity

Table 2
Bulk density (Mg m^{-3}) of soil at non-trafficked interrow position in 1992 and 1993

Year	Depth (m)	Tillage (rainfall)	DAT			
			9	19	33	46
1992	0.05	Plow (high)	0.885 Aa[a]	0.975 Aa	0.960 Aab	1.025 Aa
		Plow (low)	0.850 Ba	0.905 ABa	0.905 ABb	1.005 Aa
		No-till (high)	1.045 Aa	0.960 Aa	1.070 Aa	1.220 Aa
		No-till (low)	0.890 Ba	0.950 ABa	0.765 Bc	1.200 Aa
	0.15	Plow (high)	1.240 Aa	1.320 Aa	1.205 Aa	1.465 Aa
		Plow (low)	1.205 Aa	1.175 Aa	1.225 Aa	1.285 Aa
		No-till (high)	1.285 Aa	1.380 Aa	1.207 Aa	1.360 Aa
		No-till (low)	1.255 Aa	1.095 Aa	1.135 Aa	1.260 Aa
			8	35	66	81
1993	0.05	Plow (high)	0.975 Ba	1.345 Aa	0.955 Ba	0.910 Bab
		Plow (low)	1.040 Aa	1.050 Aa	1.300 Aa	1.100 Aa
		No-till (high)	1.010 Aa	1.370 Aa	1.325 Aa	0.790 Aab
		No-till (low)	0.990 Aa	1.180 Aa	0.985 Aa	0.740 Ab
	0.15	Plow (high)	1.140 Ba	1.615 Aa	1.190 Ba	1.310 Ba
		Plow (low)	1.270 Aa	1.485 Aa	1.685 Aa	1.370 Aa
		No-till (high)	1.390 Ba	1.360 Ba	1.820 Aa	1.280 Ba
		No-till (low)	1.565 Aa	1.400 Aa	1.255 Aa	0.985 Aa

[a] Values with the same upper case letters in a row are not significantly different among sampling days at $\alpha = 0.05$. Values with the same lower case letters in a column are not significantly different between tillage/rainfall treatments within each depth in the same year at $\alpha = 0.05$.

Table 3
Volume fraction of pores with radii greater than 386 μm and between 102 and 386 μm at non-trafficked interrow position in 1992 and 1993

Depth	Tillage (rainfall)	DAT			
		9	19	33	46
1992					
Pore radii >386 μm					
0.05 m	Plow (high)	0.045 Aa[a]	0.050 Aa	0.080 Aa	0.050 Aa
	Plow (low)	0.060 Aa	0.060 Aa	0.045 Aa	0.060 Aa
	No-till (high)	0.025 Ba	0.090 Aa	0.025 Ba	0.010 Ba
	No-till (low)	0.030 Aa	0.050 Aa	0.020 Aa	0.030 Aa
0.15 m	Plow (high)	0.015 Aa	0.010 Aa	0.010 Aa	0.015 Aa
	Plow (low)	0.015 Aa	0.005 Aa	0.010 Aa	0.005 Aa
	No-till (high)	0.015 Aa	0.015 Aa	0.005 Aa	0.010 Aa
	No-till (low)	0.010 Aa	0.045 Aa	0.010 Aa	0.005 Aa
Pore radii between 102 and 386 μm					
0.05 m	Plow (high)	0.12 Aa	0.10 Aa	0.11 Aa	0.11 Aa
	Plow (low)	0.14 Aa	0.14 Aa	0.13 Aa	0.14 Aa
	No-till (high)	0.10 Aa	0.11 Aa	0.07 Aa	0.05 Ab
	No-till (low)	0.09 Aa	0.08 Aa	0.11 Aa	0.06 Aab
0.15 m	Plow (high)	0.05 Aa	0.02 Aa	0.02 Aa	0.03 Aa
	Plow (low)	0.03 Aa	0.01 Aa	0.02 Aa	0.01 Aa
	No-till (high)	0.03 Aa	0.02 Aa	0.01 Aa	0.01 Aa
	No-till (low)	0.02 Aa	0.04 Aa	0.02 Aa	0.04 Aa
		8	35	66	81
1993					
Pore radii >386 μm					
0.05 m	Plow (high)	0.110 Aa	0.120 Aa	0.105 Aa	0.095 Aa
	Plow (low)	0.090 Aa	0.100 Aa	0.085 Aa	0.065 Aa
	No-till (high)	0.055 Aa	0.045 Aa	0.075 Aa	0.100 Aa
	No-till (low)	0.050 Aa	0.120 Aa	0.080 Aa	0.100 Aa
0.15 m	Plow (high)	0.040 Aa	0.015 Ba	0.020 ABa	0.010 Bab
	Plow (low)	0.020 Aa	0.015 Aa	0.01 0Aa	0.010 Aab
	No-till (high)	0.020 Aa	0.035 Aa	0.020 Aa	0.000 Ab
	No-till (low)	0.015 Aa	0.020 Aa	0.020 Aa	0.015 Aa
Pore radii between 102 and 386 μm					
0.05 m	Plow (high)	0.10 Aa	0.11 Aa	0.11 Aa	0.10 Aa
	Plow (low)	0.08 Aab	0.13 Aa	0.08 Aa	0.08 Aa
	No-till (high)	0.08 Aab	0.06 Aa	0.07 Aa	0.14 Aa
	No-till (low)	0.05 Ab	0.11 Aa	0.10 Aa	0.13 Aa
0.15 m	Plow (high)	0.03 Aa	0.01 Aa	0.00 Aa	0.00 Aa
	Plow (low)	0.02 Aa	0.01 Aa	0.00 Aa	0.00 Aa
	No-till (high)	0.01 Aa	0.03 Aa	0.00 Aa	0.00 Aa
	No-till (low)	0.04 Aa	0.01 Aa	0.02 Aa	0.00 Aa

[a] Values with same upper case letters in a row are not significantly different among sampling days at $\alpha = 0.05$. Values with the same lower case letters in a column are not significantly different between tillage/rainfall treatments within each depth in the same year at $\alpha = 0.05$.

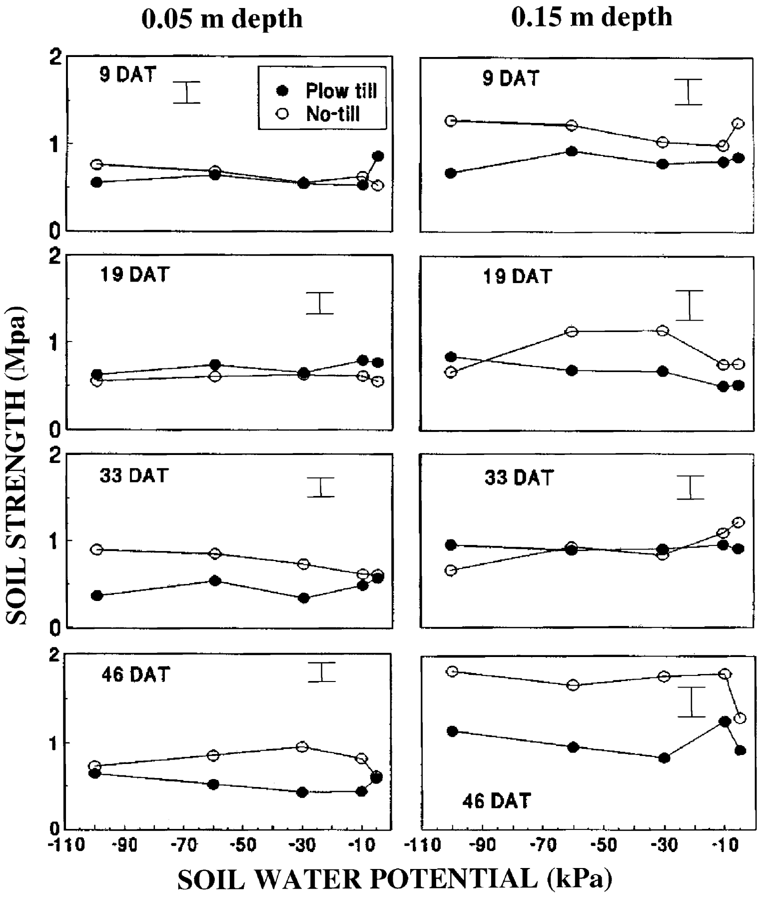

Fig. 1. Average soil strength at row position in 1992 for different water potentials and DAT for the 0.05 and 0.15 m depths. Bars indicate standard errors for mean values.

compared with bulk soil measurements such as shear and tensile strengths (Lloyd and Collis-George, 1982). Soil strength at the row position for different soil water potentials are presented in Figs. 1 and 2. Non-trafficked interrows yielded similar plots as the trafficked interrow positions (Karunatilake, 1996), and hence are not shown. Analysis of variance showed that rainfall effects were not significant in both years, while tillage effects were significant only in 1992. Alfalfa plowdown and secondary tillage were performed under adequately dry soil water levels in 1992 and consequently good tilth was established in PT plots. This lead to lower soil strength under PT compared with NT. In contrast, tillage in 1993 was performed under suboptimal soil water conditions due to extended spring precipitation where part of the plow layer was in the plastic consistency state. Soil aggregates tend to remain separated when tillage is done under sufficiently dry soil conditions, but amalgamate into unstable clods when tilled while too wet, resulting in large soil clods under PT after tillage (Cresswell et al., 1991), which might explain the lack of tillage effects on penetration resistance in 1993. Although average soil strength in PT generally was lower than in NT, strength of individual soil clods was often similar (data not shown). Larger clods tend to disintegrate upon drying, but this was not observed in this study, presumably due to intergranular cohesion within clods resulting from high clay content. The micropenetrometer probe size may in part be responsible for limited differences between tillage treatments. Bradford (1980) observed that smaller

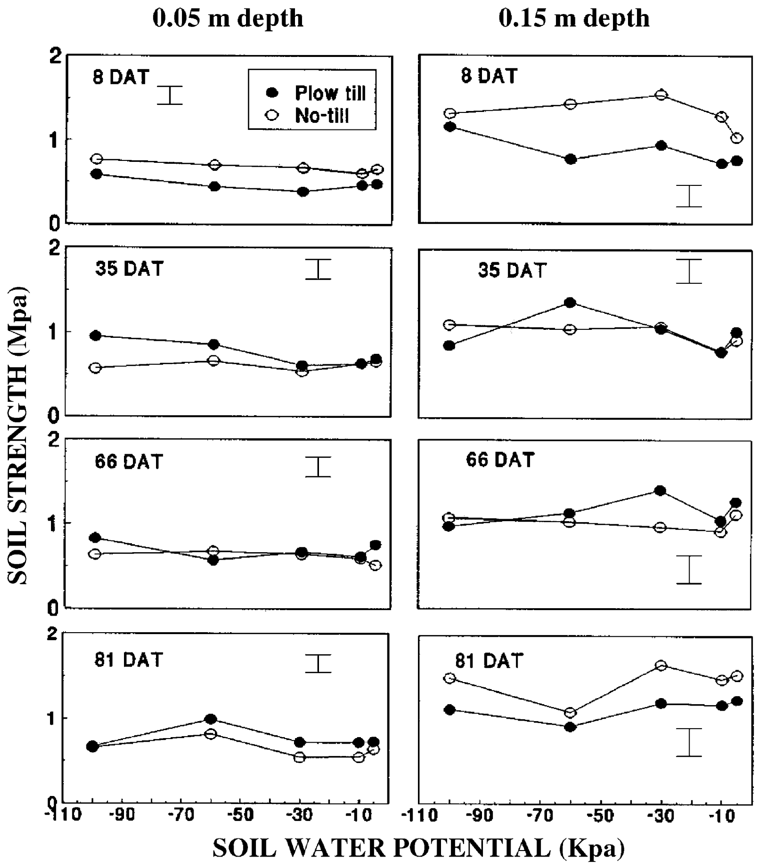

Fig. 2. Average soil strength at row position in 1993 for different water potentials and DAT for the 0.05 and 0.15 m depths. Bars indicate standard errors for mean values.

probes are more sensitive to planes of weakness in a structured soil. Since larger probes compress and shear a larger volume of soil, they are less capable of detecting smaller cracks or voids. Comparing with what other researchers have used, e.g. a 150 μm diameter probe by Grant et al. (1985), the probe size used in this study was relatively large (2 mm diameter). Taken into account the basic aggregate size of 3.5 mm in this soil (discussed later), smaller cracks and voids may not have been detected.

Rainfall effects on soil strength were non-significant, presumably because the soil was well-structured and the amount of rainfall applied was not enough to disintegrate soil aggregates and cause significant soil settling. Also, rain application under the wet treatment was stopped as soon as the tensiometers indicated soil saturation. This lead only to momentary saturation, which may have been limited to active macro- and mesopores (Luxmoore, 1981), and not have been long enough to neutralize intergranular cohesive forces in all pores. Nevertheless, rainfall amounts were considerable and represent above-average quantities for the early growing season at this site (Table 1) indicating that soil settling was unlikely to occur at this site under those conditions, as corroborated by infiltration measurements (van Es et al., 1999).

3.3. *Soil water potential and soil strength*

The relationship between soil strength and water potential (Figs. 1 and 2) is expected to show increasing strength with soil drying. Analysis of variance demonstrated that soil water potential did not significantly affect soil strength except for a few instances (at 0.05 m depth in row position at 33 DAT in 1992 and 35 DAT in 1993, and at 0.15 m depth in non-trafficked interrow position at 19 DAT in 1992 and 8 DAT in 1993). This unexpected lack of response may in part be explained by the separation of soil aggregates with drying, creating more failure zones with lower strength (Bradford, 1980). For dryer soils, these low-strength failure zones define the overall mechanical behavior of such well-aggregated soils (Mullins et al., 1992). We also failed to detect a relationship between soil strength and water content for this site using larger field penetrometers (12 mm diameter) and neutron probes, but measured significant negative soil strength–water content relationships for deeper undisturbed depths (0.30 and 0.45 m) during field measurements in both seasons (Karunatilake et al., 2000).

3.4. Soil aggregate size from spectral analysis

Tillage breaks soil aggregates, and causes them to be translocated and reoriented within the soil profile. The spatial arrangement of voids and aggregates will theoretically result in periodic small and large values in penetrometer readings or peaks in their spectral density pattern (Hadas and Shmulewich, 1990). For all the soil samples tested, Bartlett's Kolmogorov–Smirnov statistics (Bartlett, 1966) rejected the hypothesis that spectral densities were white noise ($\alpha = 0.01$), suggesting that real spectral patterns were present.

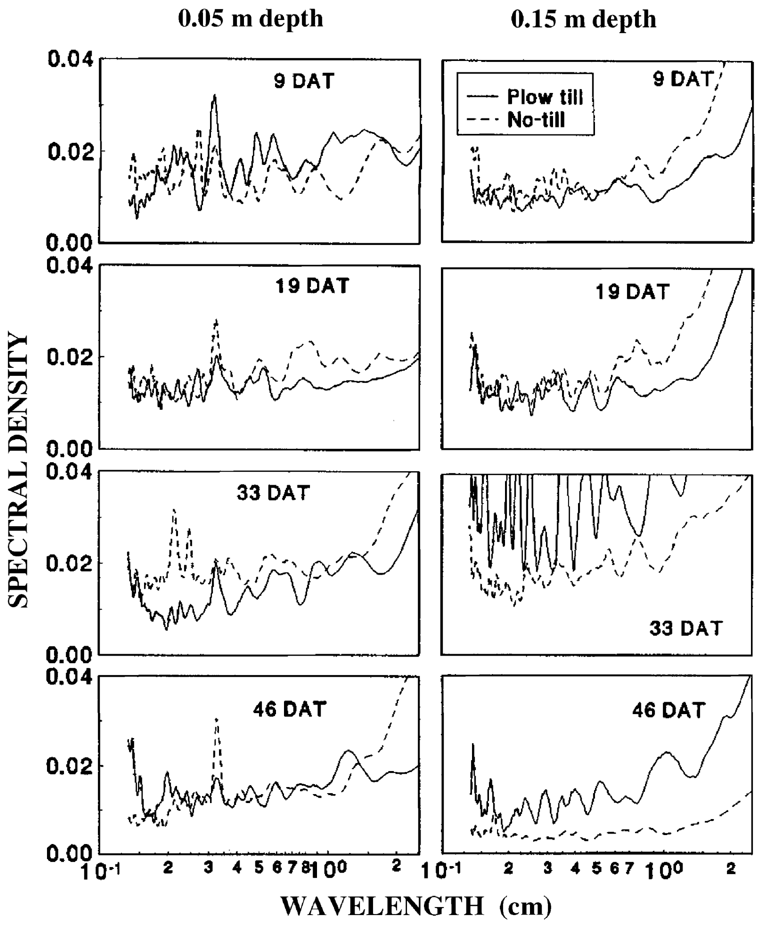

Fig. 3. Spectral densities at −100 kPa soil water potential level at row position for the 0.05 and 0.15 m depths and four DAT in 1992.

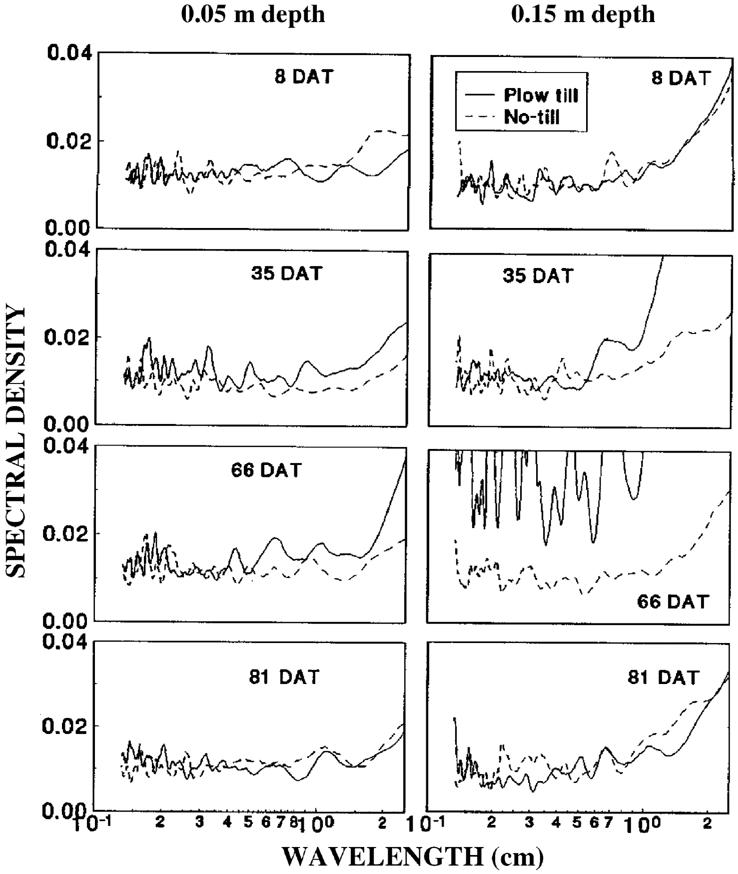

Fig. 4. Spectral densities at −100 kPa soil water potential level at row position for the 0.05 and 0.15 m depths and four DAT in 1993.

The spectral density patterns obtained under different treatments at −100 kPa soil water potential for the row position are shown in Figs. 3 and 4. Non-trafficked interrow yielded similar plots as trafficked interrow positions (Karunatilake, 1996) and are not shown. The spectral density patterns show a multitude of peaks under both PT and NT. Such peaks can be attributed to the spatial arrangement of aggregates of various sizes or to the different soil resistance at different positions along their axes (Misra, 1989). The larger wavelengths may reflect harmonics of basic wavelengths or be related to field history and not to the tillage and rainfall treatments (Hadas and Shmulewich, 1990). The concentration of clusters of peaks at low wavelengths indicates the presence of small aggregates (<4 mm). Soil disturbance from plowing is translated into many peaks observed for PT, as also found by Roseberg and McCoy (1988). The presence of these peaks at all sampling dates under PT in the present study could therefore be interpreted as stable soil structure throughout the season.

Peaks for the 0.05 m depth were generally most distinct for the 3.0–3.5 mm wavelength range under both PT and NT for all sampling dates in 1992 (Fig. 3). It can be inferred that this wavelength corresponds to the distance between failure zones, as also suggested by Grant et al. (1985). This trend was also present at the 0.15 m depth, although to a lesser extent. In 1993, spectral density patterns were less pronounced, although peaks at 3.0–3.5 mm wavelength were still observed in some cases (Fig. 4). Since this periodicity was present under both PT and NT at both depths in both years, it may be concluded that the 3.0–3.5 mm wavelength reflects the dominant size of aggregates, which were not affected by tillage (Hadas and Shmulewich, 1990).

Although the dominant aggregate size in this soil appears to be between 3.0 and 3.5 mm in diameter, visual observations showed the presence of aggregates of larger diameter (generally >10 mm), especially during the first cropping season (Karunatilake, 1996). The reason for spectral peaks to occur at lower wavelengths than the size range of visible aggregates could be due to the presence of smaller structural units within the macroaggregates (Grant et al., 1985). During subsequent growing seasons large soil aggregates fell apart into smaller ones similar to the size measured by the spectral analysis. This suggests the notion that the aggregates of size 3.0–3.5 mm reflect the basic structural units. The presence of clusters of peaks at low wavelengths could also be related to the presence of a hierarchy of smaller structural units within macroaggregates, as also observed by Taylor and Brar (1991). Spectral density patterns were less apparent in 1993 than in 1992 as tillage resulted in larger and more compacted soil clods in 1993, and less distinct failure zones.

Spectral analysis of micropenetrometer measurements failed to detect changes brought about by variable tillage and rainfall, presumably due to subtle treatments effects or the so-called “resolution effect” (Grant et al., 1985) inherent with short data series.

4. Conclusions

Analysis of soil hydraulic and mechanical behavior of a well-structured clay loam soil after conversion from alfalfa to maize showed that tillage effects were generally non-detectable. Similarly, variable soil settling from different rainfall intensities was not measured. These are presumably indicators of strong soil structure that is weakly affected by physical and hydrological processes in the first years after crop conversion. In addition, these in-depth soil physical analyses demonstrated that:

1. A well-structured surface horizon does not show the typical patterns of increasing soil strength with drying. This indicates that soil strength is mostly governed by interaggregate failure zones, which, beyond initial rapid drainage, are little affected by the increasing cohesive force from curved water menisci within soil pores. This implies that hard setting will not occur in such cases and root growth will not become inhibited upon soil drying (Karunatilake et al., 2000).
2. Spectral analysis of micropenetrometer measurements appears to provide information on the basic soil structural units that are not apparent from visual observation. The dominant spectral peak of 3.0–3.5 mm was associated with stable structural units of this size, which were initially conglomerated into larger units after conversion from alfalfa to maize, but became the dominant aggregate size after several years of row cropping.
3. Water retention in such well-structured soils shows a high contribution of large pores (generally greater than 100 μm) to the total porosity of the soil.

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