TILLAGE SYSTEMS AND NUTRIENT SOURCES AFFECTING SOIL COVER, TEMPERATURE AND MOISTURE IN A CLAYEY OXISOL UNDER CORN(1)

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SUMMARY

Tillage affects soil physical properties, e.g., porosity, and leads to different amounts of mulch on the soil surface. Consequently, tillage is related to the soil temperature and moisture regime. Soil cover, temperature and moisture were measured under corn (*Zea mays*) in the tenth year of five tillage systems (NT = no-tillage; CP = chisel plow and single secondary disking; CT = primary and double secondary disking; CT_b = CT with crop residues burned; and CT_r = CT with crop residues removed). The tillage systems were combined with five nutrient sources (C = control; MF = mineral fertilizer; PL = poultry litter; CS = cattle slurry; and SS = swine slurry). Soil cover after sowing was greatest in NT (88 %), medium in CP (38 %) and lowest in CT treatments (< 10 %), but differences decreased after corn emergence. Soil temperature was related with soil cover, and significant differences among tillage were observed at the beginning of the growing season and at corn maturity. Differences in soil temperature and moisture in the surface layer of the tilled treatments were greater during the corn cycle than in untilled treatments, due to differences in intensity of soil mobilization and mulch remaining after soil management. Nutrient sources affected soil temperature and moisture in the most intense part of the corn growth period, and were related to the variation of the corn leaf area index among treatments

Index terms: no-tillage, conservation tillage, conventional tillage, manure.

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RESUMO: *SISTEMAS DE MANEJO E FONTES DE NUTRIENTES AFETANDO COBERTURA, TEMPERATURA E UMIDADE DE UM LATOSSOLO ARGILOSO SOB MILHO*

O preparo altera as propriedades físicas do solo, entre elas a porosidade, e determina diferentes quantidades de resíduos remanescentes na superfície; consequentemente, ele pode alterar o regime de temperatura e de umidade do solo. Cobertura, temperatura e umidade do solo foram determinadas durante um ciclo da cultura de milho no décimo ano de aplicação de cinco sistemas de manejo do solo (PD = plantio direto; PE = preparo com escarificador e uma gradagem; PC = preparo com arado e duas gradagens; PQ = PC com os resíduos queimados; e PR = PC com resíduos retirados). Os sistemas de manejo foram combinados com cinco fontes de nutrientes (T = testemunha, sem aplicação de nutrientes; FM = fertilizante mineral; CA = cama de aviário; ELB = esterco líquido de bovinos; e ELS = esterco líquido de suínos). A cobertura do solo após a semeadura foi maior no PD (88 %), média no PE (38 %) e menor nos sistemas com preparo convencional (< 10 %), porém as diferenças foram reduzindo depois da emergência do milho. A temperatura do solo variou em função da sua cobertura, com diferenças significativas entre os sistemas de manejo no início do ciclo da cultura e na maturação fisiológica. Os sistemas com preparo apresentaram maior variação na temperatura e umidade do solo na camada superficial ao longo do ciclo da cultura do que o sistema sem preparo (PD), o que está diretamente relacionado com a intensidade de mobilização e quantidade de cobertura do solo remanescente após a aplicação dos tratamentos de manejo do solo. As fontes de nutrientes alteraram a temperatura e umidade do solo durante o período de maior desenvolvimento vegetativo da cultura, em razão da variação no índice de área foliar entre os tratamentos.

Termos de indexação: plantio direto, preparo conservacionista, preparo convencional, estercos, Latossolo.

INTRODUCTION

Soil temperature is a determining factor in plant production considering its effect on plant growth and development, either directly (seed germination, plant emergence, root growth, nutrient uptake and plant development) or indirectly (soil water availability and uptake, aeration, nutrient availability and decomposition of plant residues). The range of optimal soil temperatures for crop production is narrow. Crops cannot be grown below a minimum soil temperature or above an upper limit, and different strategies are needed to avoid either extreme and increase crop production (Wierenga et al., 1982).

Soil temperature regime is affected by tillage systems, in which different amounts of mulch are left on the soil surface and that also influence soil physical properties such as porosity and water content. Changes in soil cover by crop residues influence soil temperature and soil heat inputs more than alterations of soil thermal properties (Potter et al., 1985), due to the reduction in total heat input to the soil profile (Johnson & Lowery, 1985). Bragagnolo & Mielniczuk (1990) found an average reduction in the maximum daily temperature of 0.6–1.1 °C Mg^{-1} of wheat straw for maximum daily temperature at 0.05 m depth, depending on solar radiation and soil moisture. On the other hand, the higher thermal conductivity and specific heat in no-tilled soils produces deeper distribution and lower increase in soil temperature in the upper profile (Johnson & Lowery, 1985). As crop residues are retained on the soil surface, untilled soils had lower maximum temperature and variation during the growing season than tilled systems (Salton & Mielniczuk, 1995; Silva et al., 2006).

In the absence of crops, the soil water regime is primarily regulated by water infiltration and evaporation. Water infiltration and hydraulic conductivity is regulated mainly by pore-size distribution and capillary continuity, which are related to soil structure and compaction state (Hillel, 1998). Evaporation is affected by the energy available to heat and vaporize water, the readiness with which the vapor can leave the soil, and the ease of water movement through the soil to the evaporation surface (Linden, 1982).

Soil tillage and management of crop residues influence two of the three phases involved in water evaporation from soil, by modifying the surface cover and water storage capacity (Hillel, 1998). According to this author, the first stage of water evaporation (constant-rate) in wet soil is controlled by external conditions (radiation, wind velocity, air temperature and humidity, surface reflectivity and presence of mulch); at this stage, water flows freely through soil pores, similar to losses from free water surface. In the second stage (falling-rate), the evaporation rate drops progressively below the potential rate, and depends on the rate at which the gradually drying soil profile can deliver moisture to the evaporation zone. The third stage (slow-rate) is controlled almost exclusively by a dry soil surface, when evaporation is slow and constant, and water loss occurs primarily by vapor diffusion.

Under field conditions, Bragagnolo & Mielniczuk (1990) found that a high amount (7.5 Mg ha^{-1}) of wheat straw on the surface increased soil moisture by 8-10 % in the 0–0.05 m layer over uncovered treatments, due to the lower soil temperature and surface protection with straw. Such effects are more important in the summer season, when transpiration must also be considered. Less evaporation with increased soil cover allowed greater water absorption and transpiration in the vegetative cycle of bean (43 mm higher than without soil cover), and higher grain yield (Barros & Hanks, 1993).

Higher soil moisture in a no-tillage system compared to conventional tillage, mainly in the 0–0.05 m layer, results in a longer period of available soil water (Salton & Mielniczuk, 1995), which is related to finer pore-size distribution, leading to a higher saturation degree at low tension in no-tillage systems (Veiga et al., 2007; Collares et al., 2008; Streck et al., 2008). These differences resulted in 36–45 % higher water availability in no-tillage systems, due both to greater water infiltration and less evaporation, a result of crop residue retention on the surface. The root water uptake increases with reduction in soil water tension as well as increased volumetric water content at the same tension, the latter due to the direct relationship between volumetric moisture and unsaturated hydraulic conductivity (Hillel, 1998).

After relatively short periods following rainfall, no available water was found by Derpsch et al. (1991) in the 0–0.2 m layer under conventional and reduced (chisel plow) tillage systems. On the other hand, in no-tillage systems there was available water even at longer time intervals following rainfall. These authors concluded that the differences in water availability determined crop production, mainly in short periods without rainfall (3–6 weeks), and increased the sowing period (resulting in higher stand in periods of moisture deficit) and biological activity.

Water retention and availability for longer periods without rain in the different soil tillage systems and tillage practices has, however, been the subject of few studies (Melo Filho & Silva, 1993; Collares et al., 2006). Melo Filho & Silva (1993) found higher water contents at depths of 0.25 and 0.75 m in no-tillage than under conventional tillage in the first month of corn growth and observed increasing water contents under conventional tillage thereafter. The authors associated this behavior with the breaking of capillary continuity promoted by surface soil mobilization in conventional tillage resulting in lower evaporation rates compared with no-tillage, where capillary continuity remained stable. As a result, the vegetative growth of crops under no-tillage was greater at the beginning of the dry period associated with increased evapotranspiration rates, thus reducing water contents in the layer explored by the roots.

The possibility of using conservation soil management systems to grow crops in areas with severe water stress was studied by Aase & Pikul (1995) in a long-term experiment in the Great Plains of northern USA (average rainfall in the growing period 212 mm). The authors reported that direct sowing of winter cereal was advantageous over the traditional systems of the region (fallow during one growing season to store water, and sowing in the following year) for improved crop production, water use efficiency, and physical and chemical soil characteristics.

The substitution of mineral fertilizers by manure to supply crops with nutrients has been encouraged in regions where this material is available, to reduce production costs. Besides nutrient supply, long-term application of manure can increase the soil organic matter content and biological activity, affecting soil physical properties such as soil bulk density, porosity and water retention (Nyakatawa et al., 2001). Effects on physical properties in the short term, however, are only significant if high manure amounts are applied to the soil, especially when it is used to discharge these materials (Weil & Kroontje, 1979).

Previous studies of temperature and water retention in tillage systems have usually focused on some specific periods of the crop cycle, using destructive sampling for moisture determination. This study was performed to determine relationships between soil cover, soil temperature and water retention in a corn growing season, after the longstanding use of tillage systems associated with nutrient sources.

MATERIAL AND METHODS

This study was conducted in the tenth year of a field experiment at the Epagri Experimental Station of Campos Novos (Campos Novos, SC, Brazil, 27 ° 24 ' S, 51 ° 13 ' W; 970 m asl). The soil is a Typic Hapludox or a Nitossolo Vermelho according to the Brazilian classification, with 706 g kg^{-1} clay, 18.4 g kg^{-1} organic C, and high base saturation in the Ap horizon (0–23 cm).

Crops were sown in three-year rotation of grain in the spring/summer and cover crops in autumn/winter season. The annual sequence consisted of: rye (*Secale cereale*)/soybean (*Glycine max*), common vetch (*Vicia sativa*)/corn (*Zea mays*), and black oat (*Avena strigosa*)/black bean (*Phaseolus vulgaris*). In the tenth year, common vetch and black oat (45 and 25 kg ha^{-1}, respectively) were sown in April and a double-cross corn hybrid (4.5 plants m^{-1}, 0.7 m inter row) was sown at the end of October.

The main treatments consisted of a combination of soil tillage and residue management, namely: (NT) no-tillage; (CP) chisel plow and single secondary disk harrowing; (CT) primary and double secondary disking; (CTb) CT with crop residues burned; and (CTr) CT with crop residue removed from the field. They were established annually in plots 6 m wide and 30 m long, transverse to the slope, before sowing of Spring/Summer crops. The chisel and primary disking (in conventional tillage) plowed the soil down to depths of 0.25 and 0.15 m, respectively. Winter cover-crops were sown in Autumn using a direct drilling machine. A four-wheel-drive tractor weighing approximately 4.0 t was used for the primary tillage operations (i.e. primary disking and chisel plow) and a two-wheel tractor weighing approximately 2.9 t was used for the secondary tillage operations (i.e. secondary disking) and sowing. Only soybean was harvested mechanically, with a combine harvester (weight 10 t).

Nutrient source treatments consisted of: (C) control (zero nutrient application); (MF) mineral fertilizer supplied according to official recommendations for each crop (CFS RS/SC, 1995); (PL) 5 t ha^{-1} y^{-1} of wet poultry litter; (CS) 60 m^3 ha^{-1} y^{-1} of cattle slurry; and (SS) 40 m^3 ha^{-1} y^{-1} of swine slurry. Nutrient sources were applied just before the summer crop sowing, in plots 6 m wide and 30 m long, transverse to soil tillage systems (i.e. in the slope direction) in each block, before the secondary tillage. The experiment design was a 5 x 5 factorial, with 25 treatment combinations and three replications, applied in a subdivided randomized block design.

Soil cover was determined based on digital pictures taken weekly in the first stage of corn growth (from sowing to 53 days after sowing – DAS). After this time, cover was no longer measured since corn height was expected to reduce the accuracy of this determination. On a computer screen, a 10 x 10 grid of small circles (i.e. 100 circles) was placed over the digital pictures, and soil cover (straw or corn leaves) was determined. When > 50 % of a circle was filled by straw or leaf, the circle was considered covered, and the sum of covered circles corresponded to soil cover percentage.

Leaf area index of one representative plant per plot was measured weekly, from emergence to beginning of flowering (66 days after emergence), when determinations were suspended because of a hail event that damaged the leaves. The leaf area index (*LAI*, m^2 m^{-2}) was calculated from the length and width of photosynthetically active leaves, using the following equation:

$$LAI = \left[\sum_{1=1}^{n} (Li * Wi * 0.75) * P \right] \qquad (1)$$

where L is the leaf length (m); W the leaf width (m); P corn population (plants m^{-2}); i number of leaves; n number of photosynthetically active leaves; and *0.75* corn leaf shape factor (Zhang & Brandle, 1997).

Soil temperature was measured at a depth of 0.05 m in corn interrows for all combinations of soil tillage treatments and nutrient sources in block 2 of the experiment (25 plots), and at depths of 0.025 and 0.10 m in all soil tillage systems of mineral fertilizer sources in the same block (five plots), using mercury-thermometers. Soil temperature was recorded daily at 3:00 pm, under sunny or partially sunny conditions. Soil temperature was read hourly for 24 h of one sunny day, 12 DAS. Air temperature and rainfall were measured at a weather station, installed at a distance of 100 m from the experiment.

The instantaneous volumetric water content was determined by Time Domain Reflectometry (TDR) using a Soil moisture Equipment Corp (TRASE Systems, 1996). Waveguide connectors with two waveguides (length 0.23 m, diameter 0.005 m) spaced 0.05 m apart, were introduced perpendicularly into the soil in all plots. Similar waveguides were introduced horizontally at depths of 0.05 and 0.15 m, and perpendicularly in the 0.23–0.46 m layer in plots with combinations of mineral fertilizer treatments with all soil tillage systems. Measurements were made every 2 or 3 days. The transit time of electromagnetic waves was read in waveguides (Δt) at the laboratory from the graphics display saved in the TDR device during measurements. Values of the apparent dielectric constant of the soil (Ka) were calculated using the equation:

$$K_a = (c\Delta t / L)^2 \qquad (2)$$

where c is the velocity of the electromagnetic wave emitted (0.3×10^9 m s^{-1}); Δt the transit time of electromagnetic wave in waveguides (x 10^{-9} s); and L the length of waveguides (cm).

To ensure field-like measurements, a curve was calibrated specifically for this soil based on volumetric soil moisture data and Ka for a large range of soil moisture contents (Figure 1). The polynomial equation resulting from this calibration was used to calculate volumetric soil moisture from Ka by equation (2).

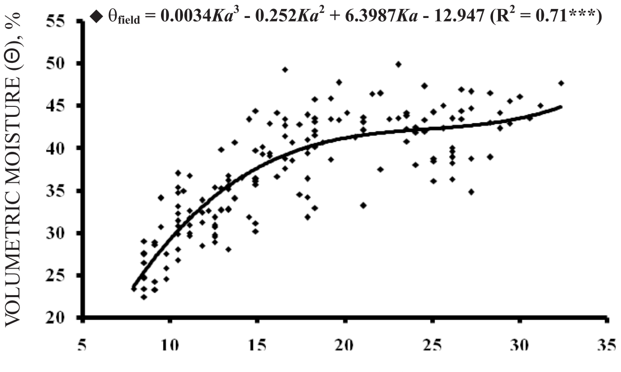

Figure 1. Correlation between apparent dielectric constant of the soil (Ka) measured by Trase System, TDR, with volumetric moisture (θ) in a clayey Oxisol.

Variances among soil tillage and nutrient sources were quantified by ANOVA. Mean differences were compared using the Tukey test ($p < 0.05$) or least-square means, following the general linear model procedure.

RESULTS

Soil cover

Soil residue cover after tillage and sowing operations was 88 % in no-tillage (NT), 38 % in chisel plow (CP) and less than 10 % in conventional tillage (CT, CTr and CTb) treatments (Figure 2). After corn emergence, when soil cover was the sum of residue and corn leaves covering, total cover remained the same at the time of measurement, i.e. from planting until 55 days after planting, in NT. It however increased in CP and CT treatments. Differences in soil cover among treatments were observed throughout the period of measurement.

Among nutrient sources, differences in soil cover were observed from 30 days after sowing up to maturity (Figure 2). The control (C) showed lower soil cover followed by cattle slurry (CS) and mineral fertilizer (MF) treatments. Plots that received swine slurry (SS) and poultry litter (PL) were highest in soil cover at this time.

Corn growth estimated by leaf area index (LAI) was affected both by soil tillage and nutrient sources treatment, but the last had higher effect on corn leaf area index until the beginning of flowering (Figure 2). Soil tillage treatments can be divided in two groups in terms LAI: (a) treatments where crop residues are kept on the field (NT, CP and CT), with higher values; and (b) treatments with others destinations to crop residues (burned = CTb and removed = CTr), with lower values.

Soil temperature

Owing to the insignificant differences in soil temperature among conventional tillage treatments (CT, CTb and CTr), only results of tillage systems where crop residues were retained (NT, CP and CT) are discussed; even though, all were considered when statistical analysis were done.

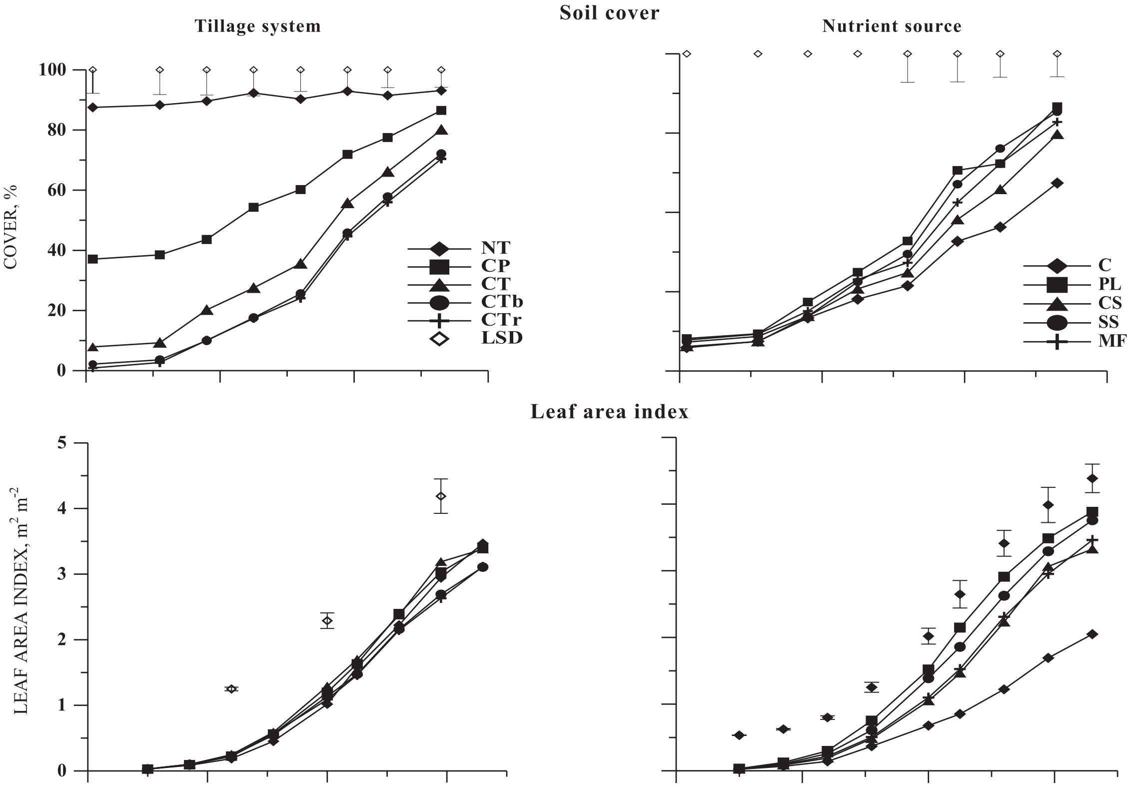

Figure 2. Soil cover by crop residues and corn leaves and leaf area index in the first stage of corn growth in five tillage systems (averaged across nutrient sources) and five nutrient sources (averaged across tillage systems). (NT: no-tillage; CP: chisel plow; CT: conventional tillage; CTb: CT with crop residues burned; CTr: CT with crop residue removed from the field; C: control; PL: poultry litter; CS: cattle slurry; SS: swine slurry; MF: mineral fertilizer; LSD: least significant difference). Vertical bars indicate significant LSD values (Tukey test, $p < 0.05$).

Hourly readings of soil temperature during a 24 h period of one sunny day, determined 12 days after sowing (DAS) is presented in figure 3. Greater differences were observed at 0.025 m depth at around 2:00 pm, when the soil temperatures at CP and CT treatments were higher than NT by about 8 °C. The differences were lower before and after 2.00 pm. At this depth, soil temperatures were higher than air temperature in almost all period. At a depth of 0.05 m the highest temperatures was around 7 °C lower than the temperature at 0.025 m in all treatments, and reached these values at around 3:00 pm, one hour later than at 0.025 m depth. Similarly near to the surface, the soil temperatures at 0.05 m deep were usually higher than air temperature. The lowest differences in soil temperature among treatments were 0.10 m deep and the highest soil temperature values were reached at around 5 pm. The maximum temperature of the three depths (0.025, 0.05 and 0.10 m) were lower in NT (33.4, 29.6 and 27.0 °C) comparatively with to CP (42.6, 32.8 and 28.6 °C) and CT (42.2, 34.7 and 30.0 °C), respectively. This resulted to respective differences of 8.8, 5.1 and 3.0 °C between NT and CT, and 9.2, 3.2 and 1.6 °C between NT and CP.

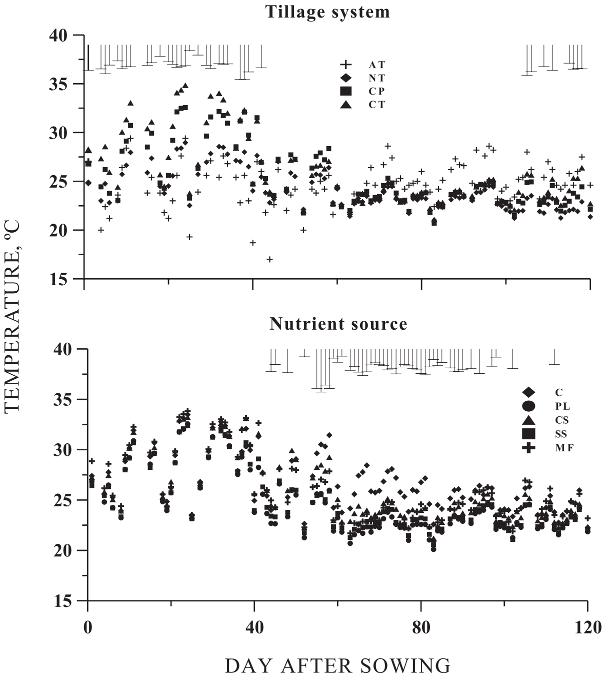

Figure 4. Air and soil temperature at 3:00 p.m., 0.05 m deep during the corn cycle in three tillage systems and five nutrient sources. (AT: air temperature; NT: no-tillage; CP: chisel plow; CT: conventional tillage; C: control; PL: poultry litter; CS: cattle slurry; SS: swine slurry; and MF: mineral fertilizer); vertical bars indicate least significant difference values (Tukey, p < 0.05).

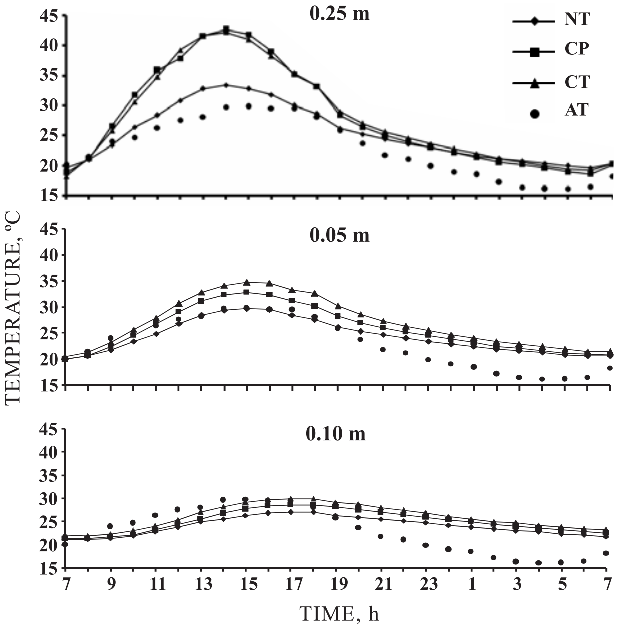

Figure 3. Air and soil temperatures at 0.025, 0.05 and 0.10 m depths over 24 h (12 days after sowing) in three soil tillage systems. (NT: no-tillage; CP: chisel plow; CT: conventional tillage; AT: air temperature).

There were differences in soil temperature, measured at 0.05 m deep at 3:00 pm, among tillage systems from sowing until around 40 DAS (Figure 4). During this period, soil temperature was highest for CT, medium for CP and lowest for NT treatment. From 40 DAS to around 100 DAS, the differences reduced significantly and the soil temperatures reduced below the air temperatures. From 100 DAS until corn maturity, there were differences in soil temperature increments at 0.05 m deep but the increase did not exceed the value of the air temperature. Variations among days were more pronounced at the beginning of the growing season. Soil temperature differences as influenced by the nutrient sources were observed from 40 to 100 DAS, and the control plot showed higher values of soil temperature than fertilized treatments plots.

The differences in soil temperature among tillage treatments at 3:00 pm were higher at 0.025 m comparatively with measurements at 0.1 m depth (Figure 5). Same trend were observed with the variation among days, especially at the beginning of the growing season.

Soil moisture

Rainfall was high and relatively well-distributed from sowing until around 80 DAS. Thereafter, rainfall amounts decreased and consequently the volumetric soil moisture content at depths that were considered (Figures 6 and 7). The volumetric soil moisture content remained nearly constant (40–45 %) in the layers 0–0.23 and 0.23–0.46 m. However, little differences were observed in the volumetric soil moisture content among tillage treatment until the

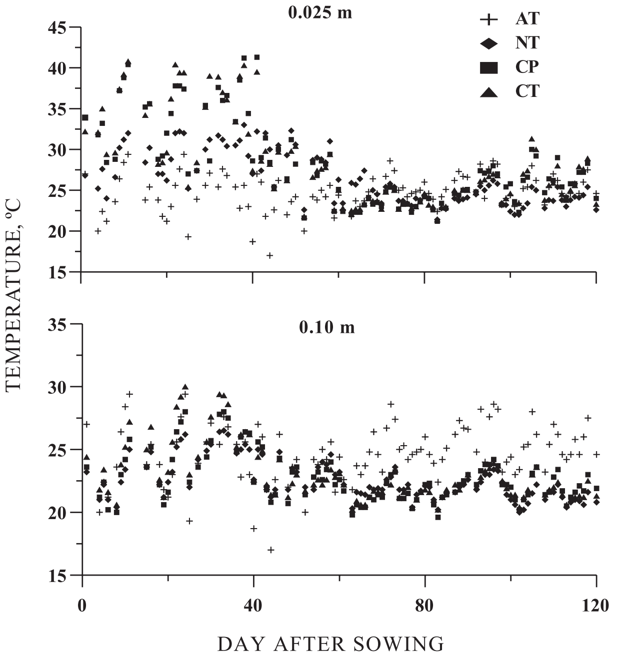

Figure 5. Air and soil temperature at 3:00 p.m., 0.025 and 0.10 m deep during the corn cycle in three tillage systems with five nutrient sources. (AT: air temperature; NT: no-tillage; CP: chisel plow; CT: conventional tillage).

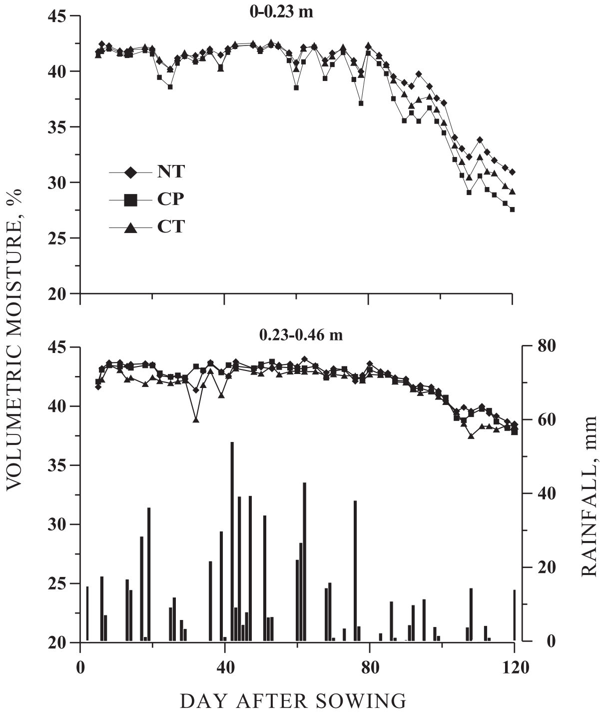

Figure 6. Volumetric moisture (curves) in two layers and rainfall (bars) during the corn cycle in three tillage systems (averaged across nutrient sources). (VM: volumetric moisture; NT: no-tillage; CP: chisel plow; CT: conventional tillage).

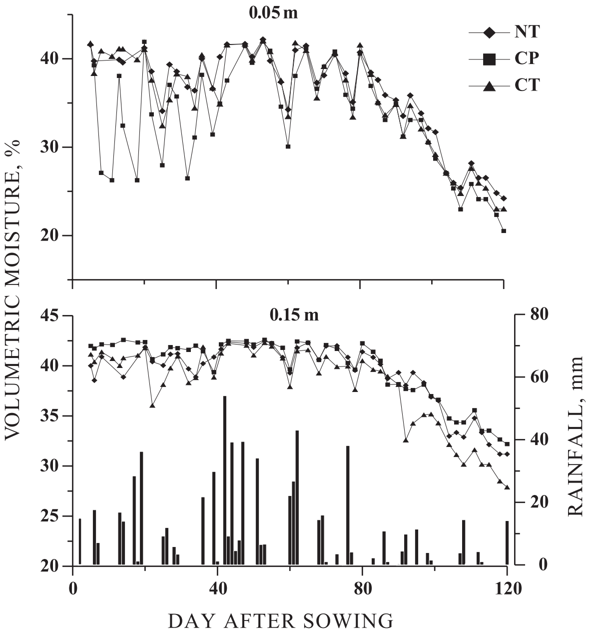

Figure 7. Volumetric moisture at 0.05 and 0.15 m depths (curves), and rainfall (bars) during the corn cycle for three tillage systems. (VM: volumetric moisture; NT: no-tillage; CP: chisel plow; CT: conventional tillage).

beginning of the dry period. In this case, there were differences among treatments and volumetric soil moisture was lower for CP in the 0–0.23 m and CT in the 0.23–0.46 m layer. During the dry period, volumetric soil moisture decreased continuously at 0–0.23 m, and reached the lowest value at corn maturity (120 DAS). Within this layer, volumetric soil moisture was highest in NT, medium in CT, and lowest in CP.

The daily variability in soil moisture contents determined with waveguides at 0.05 m deep was higher, especially in CP treatment, where volumetric soil moisture sank more than 10 % within few days after a rainfall event. On the other hand, a lower amplitude of variation in the volumetric soil moisture was observed at 0.15 m deep.

Among nutrient sources, soil moisture contents differed only during the dry period, i.e. from 80 DAS onwards among nutrient source treatments, and the volumetric soil moisture in the treatment with least crop cover (C) in the 0-0.23 m layer (Figure 8) was higher than in the fertilized treatments.

DISCUSSION

Soil cover

Soil tillage had a strong effect on soil cover with crop residues, because tillage operations with chisel plow and a secondary disking (CP) resulted in partial cover, while a primary and two secondary diskings

(CT) incorporated the residues into the soil (Figure 2). In the no-tillage system (NT), the soil was only bare in the sowing row, where the drilling machine partially incorporated the crop residues or shifted them. When crop residues were burned or removed from the field, soil cover was expected from crop leaves only.

Soil cover increased in all treatments with leaf growth after corn emergence and the differences among treatments reduced with time. The differences in soil cover among treatments tended to decrease at the time of maximum crop development (flowering), but increased again after reduction of the leaf area index due to leaf damage by hail. Soil cover in NT did not reach 100 %, since as the soil cover by leaves increased with crop growth, the soil residue cover decreased due to decomposition. The lower increment in soil cover in CP compared to CT at the time of determination was related to residue decomposition as well as leaves covering soil both with and without residue cover.

In the average across tillage treatments, the difference in soil cover among nutrient treatments from 30 DAS until measurements ended was significant. This means that soil residue cover values after tillage operations were initially not significantly different. Differences among treatments were mainly due to differences in corn development. These differences could be explained mainly by the corn N supply via residue decomposition of winter cover crops and by the cumulative effect of burning and removing crop residues on the soil chemical and physical properties, since soil moisture was high and similar among treatments in this period. At the beginning, the soil cover was least in the C treatment (without nutrient application), followed by CS treatment, but again differences tended to decrease over time. The greater effect of nutrient sources on corn growth is probably due to a higher cumulative effect on soil fertility and immediate effect of different amounts of nutrients applied at sowing. As expected, reduced corn growth was observed in the control treatment, due to lower fertility and no nutrient application at sowing. Highest corn growth in the poultry litter and swine manure treatments were related to higher cumulative soil fertility associated with the immediate effect of nutrient application.

Soil temperature

Soil temperature variation on a chosen clear day (12 DAS) showed the same trend at the three depths 0.025, 0.05 and 0.10, but the magnitude of variation and time to reach the highest and lowest values were different (Figure 3). Due to a delayed increment of soil temperature with increasing soil depth, the maximum temperatures were reached at 2:00, 3:00 and 5:00 pm, respectively, at depths of 0.025, 0.05 and 0.10 m. This was similar to findings of Silva et al. (2006), who used CT and CP after a longstanding NT system. Near the surface (0.025 m deep) the differences in soil temperature between CP and CT were less pronounced than at deeper positions, although the soil residue cover in CP was greater at this time. The lower heat input in CP compared to CT, was probably compensated for lower specific heat in the upper layer of this treatment due to its low water content, reducing the energy spent in evaporation and increasing thermal conductivity (Hillel, 1998). Since a short increase or decrease in the amplitude of soil temperature causes a significant change in crop physiology (Wierenga et al., 1982), especially during seed germination and initial root growth, it is expected that major variations in soil temperature at emergence could negatively affect crop growth and development.

The differences in soil temperature at depths of 0.025, 0.05 and 0.10 m in a corn cycle (Figures 4 and 5) can be explained mainly by differences in soil cover. At the beginning of the experiment, only residues that remained after tillage and sowing operations covered the soil, and the differences in soil temperature among tillage treatments were similar during a sunny day. When corn started to grow, residues plus corn leaves covered the soil surface. While crop cover increased, residue cover decreased, but the overall cover increased until corn flowering. During this period, soil temperature was highest for CT, medium for CP and lowest for NT treatment, as observed also by Silva et al. (2006).

Differences in soil temperature from 90 DAS until corn maturity were probably due to reduction in soil cover by corn leaves both because of hail 75 DAS (damaging leaves) and a severe drought that started afterwards, causing leaf death. At that time, soil cover of residues on the surface in NT and CP treatments accounted for differences among the soil tillage treatments in total cover and soil temperature.

Air temperature was lower than soil temperature at depths of 0.025 and 0.05 m until nearly 60 DAS (Figures 4 and 5). Thereafter, air temperature values rose above soil temperature until the end of the corn cycle. This phenomenon is related to crop development and soil cover by corn leaves, avoiding direct sunlight incidence on the soil surface and reducing total heat inputs. Air temperature was lower than soil temperature at 0.10 m deep only at the beginning of crop growth on days with lower air temperature. At this depth, soil temperature peaked around 5:00 pm rather than at 3:00 pm.

There were variations in soil temperature among treatments with different nutrient sources from 40 to 90 DAS and these were well reflected in soil cover by corn leaves, especially during flowering (Figure 4). Although there were no statistical differences in the corn cycle, the soil temperature at 0.05 m deep was lower in the PL treatment, followed by SS from the beginning to the end of the growing season. The lower soil temperature in these treatments immediately after sowing must have been caused by dry-mass production of cover crops grown before corn, a cumulative effect of nine years of applying nutrient sources. There was higher soil temperature in the C plot during the vegetative stage of corn due to reduced vegetative growth, as idicated by the lower leaf area index observed in this treatment. Close association between vegetative growth and soil temperature was also stated by Conceição et al. (1999) for cropping systems in the spring/summer season in southern Brazil.

Soil moisture

Volumetric soil moisture was closely correlated with rainfall amount and distribution pattern (Figures 6, 7 and 8). During the wet period from sowing to 80 DAS, volumetric soil moisture was regulated by soil porosity. In the dry period, the volumetric water retention capacity was highest in the NT treatment. Similar results were reported by Sidiras et al. (1983) and Salton & Mielniczuk (1995).

The highest and lowest water retention in NT and CP, respectively, can be explained by the variations among treatments in pore-size distribution. Macroporosity in the upper layers was highest in the CP treatment, followed by CT (Veiga et al., 2008). Macropores allow a rapid drainage of excess water through the soil profile and do not retain water against gravity. However, microporosity, which is related to soil water retention, was highest in the NT treatment. As a result, volumetric water retention after rainfall decreased faster in treatments with higher macroporosity and lower microporosity, and the differences remained following the reduction in soil water content. The behavior of soil moisture at 0.05 m deep (average of approximately the 0–0.10 m layer) confirmed this fact at the beginning of the corn cycle (Figure 7), when differences in macroporosity were high and significant (Veiga et al., 2008), and differences in evaporation rates alone cannot explain the high variability in volumetric soil moisture in the CP treatment. If only evaporation was involved, lower volumetric moisture would be expected in the CT treatment, where less soil was covered by residues, resulting in higher soil temperatures 0.05 and 0.10 m deep (Hillel, 1998).

The faster decrease in water content in the upper soil layer under CP treatment resulted in capillary discontinuity and reduced the evaporative water loss from the layer immediately beneath, as shown for the depth of 0.15 m (Figure 7). At this depth, soil water content was high throughout almost the entire growing season under CP, and lower for the CT treatment. This was the case because during the third phase (slow-rate), evaporation is controlled almost exclusively by the drier surface and is slow and constant, and water is lost primarily by vapor diffusion (Hillel, 1998).

Differences among nutrient source treatments were only observed in the dry period, when the volumetric moisture in treatments with less crop growth (C and CS) was higher (Figure 8). At this time, water loss by transpiration was the dominant process, and greater crop development increased evapotranspiration and consequently reduced water storage in the upper layer of the soil profile.

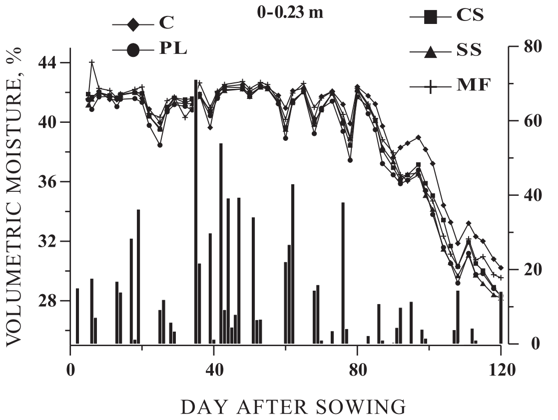

Figure 8. Volumetric moisture in the 0–0.23 m layer and rainfall (bars) during the corn cycle for five nutrient sources (averaged across tillage systems). (C: control; PL: poultry litter; CS: cattle slurry; SS: swine slurry; and MF: mineral fertilizer).

CONCLUSIONS

1. Soil residue cover after tillage was higher in untilled than in tilled treatments immediately after sowing, but differences decreased over time after corn emergence. The application of poultry litter and swine manure influenced the soil cover strongly between 40 and 90 days after sowing.

2. The variations in soil temperature among tillage treatments were significant in the entire corn growing season and is related to soil cover and dryness. Daily maximum temperatures in the untilled were lower than in the tilled treatments. Greatest differences in soil temperature induced by soil treatments with nutrient sources were observed near flowering, when vegetative growth also differed.

3. Variations of volumetric soil moisture were induced mainly by different soil cover, corn leaf area index and rainfall distribution patterns. Tillage affected the soil moisture content in the dryer period, when soil moisture was highest in the no-tillage treatment and lowest in the upper layer of plots under chisel plow. In the deeper layer measured, water storage was highest in the chisel plow treatment, followed by no-tillage and conventional tillage treatments.

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