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PROPRIEDADES DE UM NITOSSOLO VERMELHO APÓS NOVE ANOS DE USO DE SISTEMAS DE MANEJO E EFEITO SOBRE CULTURAS

TESE DE DOUTORADO

Milton da Veiga

Santa Maria, RS, Brasil

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PROPRIEDADES DE UM NITOSSOLO VERMELHO APÓS NOVE ANOS DE USO DE SISTEMAS DE MANEJO E EFEITO SOBRE CULTURAS

por

Milton da Veiga

Tese apresentada ao Curso de Doutorado do Programa de Pós-Graduação em Ciência do Solo, Área de Concentração Processos Físicos e Morfogenéticos do Solo, da Universidade Federal de Santa Maria (UFSM, RS), como requisito parcial para obtenção do grau de
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Orientador: Prof. Dalvan José Reinert

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elaborada por
Milton da Veiga

como requisito parcial para obtenção do grau de
Doutor em Ciência do Solo

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PROPRIEDADES DE UM NITOSSOLO VERMELHO APÓS NOVE ANOS DE USO DE SISTEMAS DE MANEJO E EFEITO SOBRE CULTURAS

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Data e Local da Defesa: Santa Maria, 02 de março de 2005.

A utilização continuada de diferentes sistemas de manejo determina alterações nas propriedades físicas e químicas do solo, cuja intensidade depende do tempo de uso e das condições edafoclimáticas. As propriedades físicas são mais afetadas pelos sistemas de preparo enquanto que as propriedades químicas pelo manejo dos resíduos das culturas e pela aplicação de nutrientes, resultando em respostas diferenciadas em termos de crescimento e produção das culturas. O efeito de sistemas de manejo sobre as propriedades do solo e produção de culturas foi estudado em um experimento conduzido desde 1994 na Estação Experimental da Epagri de Campos Novos, em um Nitossolo Vermelho. Os tratamentos de manejo do solo foram constituídos de uma combinação de cinco sistemas de preparo (PD = plantio direto; PE = preparo com escarificador + 1 gradagem; PC = lavração + 2 gradagens; PCq = PC com resíduos queimados e; PCr = PC com resíduos retirados) e cinco fontes de nutrientes (TT = testemunha, sem aplicação de nutrientes; AM = adubação mineral de acordo com a recomendação para cada cultura de verão; EA = 5 Mg ha^{-1} ano^{-1} de matéria úmida de cama de aviário; EB = 60 m^3 ha^{-1} ano^{-1} de esterco líquido de bovinos e; ES = 40 m^3 ha^{-1} ano^{-1} de esterco líquido de suínos). Foram avaliadas algumas propriedades físicas do solo associadas à forma da estrutura e a estabilidade de agregados após nove anos de condução do experimento e em cinco épocas durante o décimo ano; propriedades mecânicas e resistência à penetração foram determinadas em algumas combinações de tratamentos no décimo ano; temperatura e umidade do solo foram determinadas durante o ciclo da cultura do milho na safra 2003/2004, quando também foram avaliados o crescimento da parte aérea e sistema radicular do milho, bem como a produção de massa seca das culturas de cobertura de inverno e de grãos de milho. O PD apresentou maior densidade e menor macroporosidade e porosidade total logo após as operações de preparo e semeadura, mas estas diferenças reduziram com o passar do tempo. Todos os sistemas de preparo apresentaram maior estado de compactação na camada de 5 a 20 cm de profundidade após seis meses da última operação de preparo. Maior diâmetro médio de agregados secos ar foram observados nos tratamentos e profundidades com maior densidade do solo, indicando estreita associação entre estas duas variáveis. A estabilidade dos agregados, por sua vez, foi afetada por pequenas variações na umidade das amostras por ocasião da análise e maiores valores de estabilidade foram encontrados nos tratamentos de preparo com manutenção da palha na lavoura. Nas camadas superficiais do PD foi observada maior resistência mecânica à deformação, estimada pela tensão de pré-consolidação, e à penetração de raízes nas entrelinhas de semeadura sem tráfego recente. Na linha de semeadura e na entrelinha com tráfego recente as diferenças da resistência à penetração entre os sistemas de preparo foram menores. Maior temperatura do solo e maior amplitude diária foram observadas nos sistemas com maior revolvimento do solo, principalmente no início do ciclo da cultura do milho. Na camada superficial, após a ocorrência de chuvas, a umidade do solo reduziu mais rapidamente no PE, seguido do PC. No PD foi observado maior teor de umidade nesta camada mesmo em período prolongado de déficit hídrico, indicando maior armazenamento e disponibilidade de água para as plantas. Os tratamentos de aplicação de fontes de nutrientes tiveram pouco efeito sobre as propriedades físicas, hídricas e mecânicas do solo e sobre a temperatura e armazenamento de água, mas foram determinantes para o crescimento vegetativo e produção das culturas. Maiores crescimento e produção foram observados nos tratamentos com aplicação de cama de aviário e de esterco de suínos, resultado do efeito residual e imediato da aplicação destes materiais ao longo de nove anos. Entre os sistemas de preparo, a produção foi maior no PD, provavelmente em função do maior armazenamento e disponibilidade de água, já que a fertilidade do solo neste tratamento era inferior ao PE e PC ao final do nono ano.

Palavras-chaves: densidade do solo, porosidade, estabilidade de agregados, compactação, umidade do solo, temperatura do solo, milho.

ABSTRACT

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SOIL PROPERTIES AFTER NINE YEARS USE OF SOIL MANAGEMENT SYSTEMS AND EFFECT ON CROP PRODUCTION

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Place and Date: Santa Maria, March 02, 2005.

Long-term use of management systems result in alteration in physical and chemical soil properties and its intensity is related to time, soil and climate conditions. Physical properties are more susceptible to changes by the tillage system, while chemical properties by the residue management and nutrient application, resulting in different responses of crops growth and yield. This study was performed in order to evaluate long-term effect of applying soil tillage systems (NT = no-till; CP = chisel plow + 1 secondary disking; CT = primary + 2 secondary disking; CTb = CT with crop residues burned; and CTr = CT with crop residues removed from the field) and nutrient sources (C = control, without nutrient application; MF = mineral fertilizers according official recommendation for each crop; PL = 5 Mg ha^{-1} of wet matter of poultry litter; CM = 60 m^{3} ha^{-1} of liquid cattle manure; and SM = 40 m^{3} ha^{-1} of liquid swine manure) on soil properties and crop production. Soil physical and hydraulic properties and aggregate stability were evaluated at the end of ninth year of the experiment and in five sampling times throughout the tenth year; soil mechanical properties related to soil strength and penetration resistance were determined for some treatments combinations in the tenth year; soil cover, temperature and moisture were determined throughout corn cycle in 2003/2004 crop season, when corn growth and yield were also measured. No-till showed greater bulk density and lower macroporosity and total porosity after tillage and seeding operations, but the differences reduced over time. All tillage systems showed higher compaction degree at depth around 15 cm. Greater mean diameter of air-dry aggregates were found in tillage treatments and layers with higher bulk density, showing close relation between these two parameters. Wet-aggregate stability, on the other hand, was affected by aggregate moisture previous to wet-sieving determination, and greater values were found in tillage treatments where residues were kept in the field. At superficial layer of no-till was observed higher soil strength, as determined by the precompression stress, and to penetration resistance in untrafficked interrow. In seeding row and recent trafficked interrow the differences in penetration resistance among tillage systems were smaller. Higher soil temperature and daily amplitude were found in tilled treatments, mainly at the beginning of corn cycle. After rainfall events, soil moisture reduced faster in chisel plow system, followed by conventional tillage. Higher moisture content and lower water tension was found in no-till system even in long period with hydric deficits, resulting in higher water storage and availability to crops. Higher water availability seems to be the main factor in determining higher crop growth and yield in no-till treatment. Nutrient sources treatments had small effect on physical soil properties, but high effect on chemical properties and crop growth and yield. Greater growth and yield were observed with poultry litter and swine manure application, because of residual and immediate effect of nutrient application through these materials.

Key words: bulk density, porosity, aggregate stability, compaction, soil moisture, soil temperature, corn.

INTRODUÇÃO GERAL

Os sistemas de manejo utilizados em uma lavoura determinam alterações nas características físicas e químicas do solo, cuja intensidade é dependente das condições edafoclimáticas e do tempo de uso. O preparo do solo constitui-se na prática de manejo que mais altera as propriedades físicas do solo e seu efeito depende do implemento utilizado, da intensidade de seu uso e da condição de umidade por ocasião das operações. O propósito do preparo do solo é criar um ambiente favorável para o crescimento das raízes e, de forma geral, determina redução da densidade do solo e aumento da porosidade na camada preparada, com conseqüente alteração na capacidade de fluxo e armazenamento de água, de suprimento de nutrientes e de oxigênio, bem como da resistência mecânica à penetração. Esses efeitos, no entanto, são sazonais e reduzem com o passar do tempo em função da reconsolidação natural do solo determinada por ciclos de umedecimento e secagem e pela desagregação superficial do solo pelo impacto das gotas de chuva em condição de solo descoberto.

O uso continuado de um mesmo sistema de preparo pode resultar na criação de camadas compactadas abaixo da profundidade de preparo, com restrição ao crescimento radicular e fluxo de água e de ar. Na ausência de preparo (plantio direto), corre-se o risco de promover a compactação superficial progressiva em função do tráfego de máquinas pesadas sobre o solo em condições de umidade favorável à deformação plástica do solo. Por outro lado, a ausência de preparo resulta na criação de um sistema poroso mais estável e contínuo em profundidade, como resultado da atividade da mesofauna e da decomposição das raízes, promovendo condições favoráveis para o fluxo de água e de ar para camadas mais profundas e, ao mesmo tempo, aumentando a resistência mecânica à deformação e prevenindo a transmissão de tensões aplicadas superficialmente para camadas mais profundas, geralmente com menor resistência à deformação.

O preparo do solo também altera os regimes de temperatura e de umidade do solo porque determina a manutenção de diferentes quantidades de resíduos na superfície ou porque altera propriedades físicas, tais como a porosidade e a distribuição de diâmetro de poros. Sistemas de preparo com menor revolvimento do solo e manutenção de maior quantidade de resíduos na superfície, com destaque para o plantio direto, geralmente resultam em maior taxa de infiltração e menor evaporação da água da chuva, resultando em balanço hídrico favorável. No entanto, persistem dúvidas sobre a extensão de tempo sem precipitação em que a disponibilidade de água no plantio direto é maior do que nos sistemas que envolvem uma maior mobilização do solo. Isso porque, no plantio direto, a maior retenção de água (maior condutividade hidráulica do solo não saturado), a homogeneidade de características no perfil (continuidade de poros) e o maior desenvolvimento das culturas em períodos de escassez média de água, favorecem a manutenção de taxas de evapotranspiração mais elevadas que os demais sistemas, com conseqüente redução da água armazenada.

O manejo dos resíduos de colheita e a adubação constituem-se em práticas de manejo que resultam em alterações substanciais nas propriedades químicas do solo. A manutenção dos resíduos na superfície (plantio direto), a semi-incorporação (preparo com escarificador) ou a quase completa incorporação (preparo convencional) resultam em diferentes taxas de decomposição destes e de distribuição dos nutrientes no perfil do solo. A queima e, principalmente, a retirada dos resíduos da lavoura determinam uma maior exportação de nutrientes do sistema, resultando em redução de sua disponibilidade. Efeitos adversos do manejo inadequado dos resíduos e de diferentes preparos do solo sobre as propriedades físicas e químicas podem ser minimizados pela aplicação de nutrientes através de adubos minerais ou de estercos de animais.

Na região onde foi desenvolvido o trabalho, o plantio direto é utilizado em aproximadamente de 90% da área cultivada com culturais anuais, sustentando produtividades maiores do que sistemas que envolvem preparo do solo. No entanto, ainda persistem dúvidas se o estado de compactação do solo está ou não afetando o desenvolvimento radicular e a produção das culturas, principalmente por tratar-se de um solo muito argiloso e de clima úmido, com trânsito de máquinas pesadas, principalmente colheitadeiras, em condições de umidade favorável à compactação. Por outro lado, há disponibilidade de estercos de animais que podem ser aplicados em substituição ou suplementação da adubação mineral, com redução de custos para os produtores, os quais também podem promover melhorias nas propriedades físicas do solo.

Uma vez que o efeito de sistemas de manejo sobre as propriedades físicas e químicas do solo e sobre a produção das culturas é dependente das condições edafoclimáticas e do tempo de utilização, a realização de estudos de curto e de longo prazo em diversas condições permitirá a compreensão da magnitude dos efeitos de forma regionalizada, com a possibilidade de elaboração de estratégias específicas para solução de problemas que porventura venham a ser detectados.

Dentro dessa perspectiva, o estudo que constitui esta tese foi efetuado em um experimento conduzido na Estação Experimental da Epagri de Campos Novos desde maio de 1994, com o objetivo de estudar o efeito de curto e longo prazo de sistemas de manejo sobre as propriedades de um Nitossolo Vermelho e sobre a produção de culturas. Os sistemas de manejo são constituídos por uma combinação de cinco sistemas de preparo do solo e de cinco fontes de nutrientes, aplicados por ocasião da implantação das culturas comerciais de primavera/verão. As culturas comerciais de primavera/verão (milho, feijão e soja) e as de cobertura de inverno (triticale/centeio, vica comum e aveia preta) são semeadas em rotação, em ciclos de três anos.

Para realização deste estudo, foram formuladas as seguintes hipóteses:

1 – As propriedades físicas (hídricas e mecânicas) e químicas do solo são alteradas em maior magnitude pelos sistemas de manejo até a profundidade de ação dos implementos e reduzem com o tempo após preparo em função da reconsolidação natural do solo;

2 – As variações na temperatura e umidade do solo são menores nos sistemas com maior quantidade de resíduos remanescentes sobre a superfície após o preparo do solo e maiores no início do ciclo da cultura de milho em função do crescimento da cultura;

3 – As alterações nas propriedades físicas e químicas, na temperatura e na umidade do solo são determinantes para o crescimento e produção das culturas.

Para testar estas hipóteses foram desenvolvidos estudos de campo e de laboratório, cujos resultados são apresentados na forma de capítulos organizados de acordo com afinidades de determinações. Nos CAPITULOS 1 e 2 são apresentados e discutidos, respectivamente, os efeitos de curto e de longo prazo de sistemas de manejo sobre propriedades físicas e hídricas do solo e sobre a estabilidade de agregados. Resultados de compressibilidade e penetrabilidade do solo determinadas em algumas combinações de tratamentos de preparo do solo e de fontes de nutrientes são apresentados e discutidos no CAPITULO 3. Cobertura, temperatura e umidade do solo foram determinados durante um ciclo da cultura do milho e os resultados são apresentados e discutidos no CAPITULO 4. O efeito acumulado de 9 anos de utilização de sistemas de manejo do solo sobre algumas propriedades químicas que avaliam a fertilidade do solo, bem como o crescimento da parte aérea e do sistema radicular da cultura do milho e a produção de massa seca das plantas de cobertura de inverno e de grãos de milho no décimo ano de condução do experimento são apresentados e discutidos no CAPITULO 5. Em cada capítulo são apresentados os objetivos e as conclusões específicas relativos aos aspectos abordados no mesmo.

REVISÃO DE LITERATURA

O manejo utilizado em um determinado solo promove, diretamente, alterações nos atributos do mesmo, tanto na superfície como em profundidade, e, indiretamente, na relação solo-planta-atmosfera. As alterações na superfície dizem respeito à manutenção ou supressão da cobertura promovida por resíduos culturais e pela rugosidade superficial remanescente, que interferem nas taxas de infiltração, de escoamento e de evaporação de água. A infiltração de água é uma das características físicas que melhor retrata as alterações provocadas no solo pelo manejo utilizado, podendo-se prever, através do manejo, a capacidade de absorção e escoamento superficial de água.

Inúmeros estudos têm comprovado a eficiência de manejos conservacionistas do solo em aumentar a taxa de infiltração de água nas lavouras e, conseqüentemente, reduzir as perdas de água e de sedimentos em diferentes condições edafoclimáticas (Nunes Filho et al., 1987; Derpsch et al., 1991; Hernani et al., 1997; Beutler et al., 2003). Nesses estudos, as menores taxas de perda de água e de sedimentos ocorreram em sistemas que mobilizavam o mínimo possível o solo e mantinham o máximo de cobertura por resíduos culturais na superfície do mesmo, com destaque para o plantio sem preparo ou plantio direto.

As relações entre os graus de cobertura proporcionados por resíduos culturais e as perdas de água e de sedimentos foram estabelecidas em experimentos com chuva artificial (Meyer et al., 1970; Lopes et al., 1987a e 1987b; Lombardi Neto et al., 1988). Esses autores determinaram que a cobertura do solo, além de dissipar a energia cinética das gotas da chuva, se constitui em barreira física que reduz acentuadamente a velocidade do escoamento superficial e o tamanho dos agregados transportados. A redução nas perdas foi mais acentuada nos primeiros incrementos de cobertura, sugerindo uma curva exponencial entre estes parâmetros.

A cobertura do solo é o fator isolado que mais influencia na redução das perdas de sedimentos. Bertol et al. (1987) determinaram que, independente do sistema de preparo, 60% de cobertura do solo reduziu em aproximadamente 80% as perdas de sedimentos em relação à ausência de cobertura. As perdas de água, por sua vez, foram mais afetadas pelo método de preparo do que pela cobertura. Deve-se ressaltar, no entanto, que a cobertura remanescente sobre o solo após o preparo depende da quantidade de palha existente antes deste e, principalmente, das operações de preparo empregadas. Assim, quanto maior o número de operações e maior o uso de implementos de discos, menor a cobertura remanescente.

A temperatura e a umidade do solo também são influenciadas pela presença de resíduo cultural na superfície do solo. Bragagnolo & Mielniczuk (1990), estudando a influência de doses de resíduo cultural de trigo na superfície, determinaram uma redução média de 0,6 a 1,13 ºC Mg^{-1} de resíduo na temperatura máxima diária a 5 cm de profundidade, dependendo da insolação e da umidade do solo. As maiores doses de resíduos mantiveram a umidade do solo na camada de 0-5 cm de profundidade, em média de 8 a 10 unidades percentuais acima da observada no solo descoberto ou com pouca palha, estando associado à menor evaporação de água em função da menor temperatura e da proteção da superfície pela palha.

As variações na temperatura e na umidade do solo também foram estudadas em diferentes sistemas de manejo do solo. Salton & Mielniczuk (1995) determinaram que o solo sob plantio direto apresentou, ao longo do período estudado (5 meses no verão), menor temperatura máxima, menor amplitude de variação e maiores valores de umidade, ocorrendo o inverso no preparo convencional, principalmente na camada de 0-5 cm de profundidade. Dessa forma, o solo manteve-se por mais tempo na faixa de água disponível para as plantas. Resultados semelhantes foram observados por Sidiras et al. (1983), que encontraram no plantio direto um teor de água no solo, na capacidade de campo, 4 a 5 pontos percentuais superior ao preparo convencional, na camada de 0-20 cm. Essa diferença resultou em maior disponibilidade de água para as culturas no plantio direto, na ordem de 36 a 45% em relação ao preparo convencional. Os autores associaram a maior disponibilidade de água no plantio direto tanto à maior infiltração de água da chuva como à redução das perdas por evaporação, ambas relacionadas com a presença de cobertura morta sobre a superfície do solo.

Segundo Lemon (1956), existem três fases envolvidas na evaporação de água do solo e o homem pode intervir, através do manejo dos resíduos e do solo, nas duas primeiras. A primeira fase é controlada pelas condições externas próximas à superfície do solo (temperatura, velocidade do vento, umidade do ar e intensidade dos raios solares), sendo que a água flui livremente pelos poros e se comporta de forma semelhante às águas superficiais livres. A segunda fase é caracterizada pelo rápido decréscimo da taxa de evaporação no decorrer do tempo na medida em que reduz a umidade do solo e a taxa de evaporação é função linear da umidade média do solo. A terceira fase, por sua vez, é controlada quase exclusivamente pela superfície seca do solo, sendo que a evaporação é lenta e constante e a perda de água é realizada primariamente pela difusão.

Confirmando essa teoria, Bond & Willis (1970) determinaram que a superfície do solo descoberto perde o máximo de água em cinco dias (primeira fase) e em seguida sofre redução drástica da evaporação até os 10 dias (segunda fase), quando então se torna constante (terceira fase). Nesse mesmo solo, quanto maior a quantidade de palha em cobertura, menor a taxa de evaporação diária no período de evaporação máxima, sendo essa constante nesse intervalo de tempo, decaindo em menor intensidade a partir de então. A evaporação acumulada num período de 65 dias foi aproximadamente três vezes menor quando o solo recebeu significativo aporte de resíduos culturais na superfície (17,9 Mg ha^{-1}), quando comparado ao solo descoberto. Esse aspecto assume grande importância quando o solo é cultivado e é considerada, também, a transpiração das culturas. Barros & Hanks (1993) determinaram que o aumento da produção da cultura do feijoeiro no tratamento com cobertura morta em relação ao solo descoberto foi devido à menor evaporação no primeiro, que possibilitou maior absorção de água e transpiração pela cultura no período vegetativo (43 mm a mais durante o ciclo).

Derpsch et al. (1991) observaram que, em períodos relativamente curtos, já não havia água disponível nas camadas de 0-10 e 10-20 cm no preparo convencional e no cultivo mínimo. No plantio direto, somente em um período maior sem precipitação não foi detectada água disponível nessas camadas. Os autores concluíram que essas diferenças são determinantes para assegurar a produção, principalmente nos períodos curtos de estiagem (3 a 6 semanas), influenciando, também, no aumento do período útil para semeadura, redução do risco de falha de germinação e aumento da atividade biológica. Isto explica o fato de que, em condições de déficit hídrico, a população inicial de plantas no plantio direto tende a ser maior do que no preparo convencional. A manutenção de água disponível no solo por um período mais prolongado favorece sua absorção pelas sementes e, conseqüentemente, permite-lhes emergência mais uniforme.

O plantio direto, além de minimizar os efeitos de veranicos, possibilita o cultivo de cultura de sequeiro em regiões com períodos prolongados de baixa precipitação ou mesmo em regiões semi-áridas, com períodos curtos de chuvas e baixos índices pluviométricos. A retenção e disponibilidade de água no solo em período mais prolongado de estiagem, no entanto, têm sido pouco estudadas. Melo Filho & Silva (1993) determinaram, em condições de semi-árido, um maior conteúdo de água no solo manejado sob plantio direto, nas profundidades de 25 e 75 cm, durante o primeiro mês de condução do experimento e uma inversão a partir de então, quando o maior armazenamento de água foi observado no preparo convencional. Os autores associaram esse comportamento à quebra da capilaridade promovida pela mobilização do solo no preparo convencional, que poderia promover menor taxa de evaporação nesse sistema do que no plantio direto onde esta capilaridade foi mantida. Além disso, as plantas no plantio direto, em função do maior desenvolvimento vegetativo, aumentaram as taxas de evapotranspiração, consumindo mais água e reduzindo mais acentuadamente o conteúdo de água no solo a partir da redução dos índices pluviométricos.

A possibilidade de efetuarem-se cultivos anuais em condições de extrema escassez de água, através do uso de sistemas conservacionistas de manejo do solo, foi estudada por Aase & Pikul (1995) em um experimento de longa duração nas Grandes Planícies no norte dos EUA, onde a média de precipitação anual situa-se ao redor de 360 mm, sendo 212 mm na estação de crescimento das culturas. Os autores determinaram que o plantio anual de cereais em plantio direto constituiu-se em uma alternativa melhor do que o sistema tradicional (pousio em um ano para armazenamento de água e semeadura de cereal no outro) do ponto de vista de produção, eficiência do uso da água e características químicas e físicas do solo.

O potencial matricial, o teor de água no solo e as funções de condutividade hidráulica do solo são os principais atributos que determinam a disponibilidade e o fluxo de água no perfil. As variáveis mais utilizadas para descrever o fluxo de água no solo incluem a taxa de infiltração, a condutividade hidráulica, o teor de água no solo e a tensão de água no solo. Alta condutividade determina rápido deslocamento de água no solo, sendo importante, por exemplo, para a taxa de infiltração de água das chuvas (solo saturado) e para o fluxo de água para as raízes das plantas (solo não saturado). A condutividade hidráulica do solo é uma função de suas características, tendo grande influência a distribuição do diâmetro de partículas e a porosidade. A porosidade, por sua vez, depende do grau de adensamento das partículas e do estado de agregação do solo, bem como da existência de porosidade biológica.

Os sistemas de manejo do solo alteram as características físicas associadas à condutividade hidráulica do solo. Derpsch et al. (1991) observaram que todos os métodos de preparo levaram a uma compactação do solo em relação às condições naturais, medida pelo aumento da densidade do solo. No plantio direto as maiores densidades foram observadas na camada de 0-20 cm e, no preparo convencional, na camada de 20-30 cm. Valores intermediários foram encontrados no preparo com escarificador. Os autores ponderaram que, no plantio direto, corre-se o risco de se promover uma compactação superficial progressiva com o tráfego de máquinas pesadas (caminhões e colheitadeiras) sobre a área, em condições de umidade inadequada, podendo resultar em dificuldades para o desenvolvimento do sistema radicular das culturas. O efeito do tráfego de equipamento pesado (10 Mg) sobre um Argissolo, manejado sob plantio direto, foi estudado por Streck et al. (2004), que determinaram aumento da densidade do solo e resistência à penetração até a profundidade de 15 com duas passadas do equipamento. O efeito de compactação pelo tráfego de máquinas pode ser minimizado aumentando-se a matéria orgânica do solo (Free et al., 1947), mantendose grande quantidade de resíduos na superfície do solo (Acharya & Sharma, 1994), reduzindo-se a aplicação de pressão sobre o solo (menor número de passadas, máquinas mais leves e, ou dotadas de pneus de maior área de contato e baixa pressão) e evitando-se o tráfego em condições de umidade que favoreça a compactação.

Centurion & Demattê (1985) observaram que, com exceção do plantio direto, os sistemas de preparo conservacionista e convencional induziram a formação de camadas compactadas, resultando em menor taxa de infiltração de água. Aquele sistema propiciou ao solo maior homogeneidade estrutural, apresentando, no período chuvoso, maior retenção de água. Entretanto, no período seco os autores relataram ter ocorrido o inverso. Resultado semelhante foi obtido em um solo arenoso por Abreu et al. (2003), o qual observou que a densidade do solo e a resistência mecânica à penetração são mais uniformemente distribuídos no perfil do solo sob plantio direto, refletindo-se em uma maior infiltração e maior armazenamento de água. Esse autor observou, também, que o rompimento mais eficiente de camadas compactadas na subsuperfície foi obtido pelas raízes de plantas (Crotalária) do que pelo uso de escarificador.

O volume de poros do solo está associado ao grau de compactação do mesmo. Quanto maior a compactação de um mesmo solo, menor o volume total de poros e maior a microporosidade. Fernandes et al. (1983) observaram no plantio direto uma distribuição mais uniforme dos poros em profundidade, refletindo-se a estruturação natural do solo. Nesse estudo, as maiores alterações na densidade e porosidade ocorreram nas camadas superficiais, sendo que de 0-10 cm o plantio direto apresentou menor quantidade de poros com diâmetro maior que 0,15 mm. Apesar de apresentar uma menor porosidade total, o solo manejado sob plantio direto apresenta maior continuidade de poros, principalmente pela presença de porosidade biológica, oriunda da ação da mesofauna do solo e da decomposição das raízes das culturas.

A maior proporção de microporos encontrados no plantio direto pode determinar, em períodos prolongados de precipitação, associado à baixa evapotranspiração, condições de drenagem deficiente e criação de ambiente redutor na zona de crescimento das raízes, com reflexos sobre o desenvolvimento inicial das culturas (Chan & Heenan, 1996), podendo dificultar o crescimento radicular e favorecer a ocorrência de doenças radiculares. Além disso, a condutividade do solo saturada é reduzida, favorecendo o escoamento superficial de água em chuvas de alta intensidade.

A aplicação de dejetos animais para fornecimento de nutrientes em substituição aos adubos minerais tem sido estimulada nas regiões onde há concentração de criação de animais, em função de se constituírem em fontes relativamente baratas tanto de macro como de micronutrientes (Scherer & Bartz, 1982; Scherer et al., 1984; Nyakatawa et al., 2001). Além do fornecimento de nutrientes, a aplicação continuada de dejetos pode resultar, a longo prazo, no aumento da matéria orgânica e na atividade biológica, com reflexos sobre as propriedades físicas como densidade do solo, porosidade e retenção de água (Nyakatawa et al., 2001). Efeitos significativos sobre as propriedades físicas podem ser observadas a curto prazo quando doses elevadas de dejetos são aplicadas no solo tendo em vista o uso deste para descarte dos materiais (Weil & Kroontje, 1979).

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CAPITULO 1. ATRIBUTOS FÍSICOS E HÍDRICOS DE UM NITOSSOLO VERMELHO APÓS CURTO E LONGO PRAZO DE APLICAÇÃO DE SISTEMAS DE PREPARO E DE FONTES DE NUTRIENTES.

1.1 Resumo

As propriedades físicas e químicas do solo são afetadas pelo preparo do solo porque ele promove alterações na estrutura deste, geralmente reduzindo a densidade e aumentando a porosidade. A magnitude das alterações varia com a natureza do solo, método de preparo e conteúdo de água quando de sua realização, mas este efeito reduz com o tempo devido à reconsolidação natural do solo. O efeito de curto e de longo prazo de cinco sistemas de preparo do solo (PD = plantio direto; PE = escarificação + gradagem; PC = aração + 2 gradagens; PCq = PC com resíduos queimados e; PCr = PC com resíduos retirados) associados com cinco fontes de nutrientes (T = testemunha; AM = adubação mineral de acordo com a recomendação para manutenção de cada cultura; EA = 5 Mg ha^{-1} a^{-1} de cama de aviário, base úmida; EB = 60 m^3 ha^{-1} a^{-1} de esterco líquido de bovinos e; ES = 40 m^3 ha^{-1} a^{-1} de esterco líquido de suínos) sobre algumas propriedades físicas e hidráulicas do solo foi determinado em um Nitossolo Vermelho com alto conteúdo de argila, no Sul do Brasil. A densidade do solo (Ds), a porosidade total (Pt) e parâmetros obtidos da curva de retenção de água (macro e microporosidade, retenção de água na capacidade de campo e ponto de murcha permanente), foram determinados depois de nove anos e em cinco épocas de coleta durante o décimo ano de experimentação. A condutividade hidráulica do solo saturado foi determinada em três épocas de coleta durante o ciclo da cultura do milho. As propriedades físicas e hidráulicas do solo foram dependentes do sistema de preparo e da ‘epoca de amostragem. Maiores diferenças entre os sistemas de preparo foram observadas imediatamente depois da semeadura e reduziram com o passar do tempo. O PD mostrou maior Ds e microporosidade na camada superficial do que os tratamentos com preparo considerando todas as épocas de coleta efetuadas no décimo ano, mas não na coleta efetuada após nove anos. Nesta coleta, efetuada seis meses após a última operação de preparo, maiores valores de Ds foram observados nas camadas de 5-10 e 12-17 cm em todos os sistemas de preparo, indicando a presença de uma camada compactada nesta profundidade. O PD e o PE apresentaram maior volume de poros de maior diâmetro (> 50 μm) nas camadas de 0-5 e 12-17 cm e o PC apenas na camada de 0-5 cm. A macroporosidade reduziu com o passar do tempo após as operações de preparo, mas não resultou em aumento da microporosidade. A condutividade hidráulica do solo saturado foi maior na camada superficial (1,0 – 8,5 cm) nos tratamentos com preparo. Não foram observadas diferenças significativas nas propriedades físicas e hídricas entre as fontes de nutrientes.

Palavras chaves: preparo do solo, densidade do solo, porosidade do solo, condutividade hidráulica do solo saturado.

SHORT AND LONG-TERM EFFECTS OF SOIL TILLAGE SYSTEMS AND MINERAL AND ORGANIC AMMENDMENTS ON PHYSICAL AND HYDRAULIC PROPERTIES OF A HAPLORTHOX IN SOUTHERN BRAZIL

1.2 Abstract

Soil physical and hydraulic properties are affected by soil tillage because it promotes changes in soil structure, generally decreasing soil bulk density and increasing soil porosity. The magnitude of the changes varies with the nature of the soil, tillage method and soil water content, and decrease over time after tillage. The short and long-term effects of applying five soil tillage (NT = no-till; CP = chisel plow + 1 secondary disking; CT = primary + 2 secondary disking; CTb = CT with crop residues burned; and CTr = CT with crop residues removed from the field) associated with five nutrient sources (C = control, without nutrient application; MF = mineral fertilizers according official recommendation for each crop; PL = 5 Mg ha^{-1} y^{-1} of wet-matter of poultry litter; CM = 60 m^3 ha^{-1} y^{-1} of slurry cattle manure; and SM = 40 m^3 ha^{-1} y^{-1} of slurry swine manure) on some physical and hydraulic properties were determined in an Oxisol with high clay content, in Southern Brazil. Bulk density (BD), total porosity (TP), and parameters derived from the water retention curve (macro and microporosity, water retention at field capacity, and permanent wilting point) were determined after nine years and at five sampling times during the tenth year of the experiment. Saturated hydraulic conductivity was determined at three sampling times during the corn cycle. Soil physical and hydraulic properties were tillage and time dependent. Greater differences among tillage treatment were observed after seeding and reduced over time. NT showed greater BD and microporosity than tilled treatments in the superficial layer considering all sampling times during the tenth year, but not at sampling time after nine years. In that time (six months after last tillage), greater values of BD were observed at 5-10 and 12-17 cm layers, showing the presence of a compacted layer in all tillage treatments at this depth. NT and CP showed greater volume of larger pores (> 50 μm) at 0-5 and 12-17 cm layers and CT only at 0-5 cm layer. Macroporosity reduced over time after plowing but did not result in increasing volume of micropores. Soil saturated hydraulic conductivity was greater in tilled treatments only at 1.0 – 8.5 cm layer. No differences were found in physical and hydraulic properties among nutrient sources treatments.

Keywords: soil tillage, bulk density, soil porosity, saturated hydraulic conductivity.

1.3 Introduction

Soil physical factors which directly affect plant growth and yield (temperature, mechanical resistance, water and oxygen availability) are determined by internal soil properties, conditions above soil surface, as well as by the soil-crop-atmosphere relationship (Forsythe, 1967). Of the four factors, water is the dominant controlling factor and the others three are affected by water content (Letey, 1985). Soil texture, bulk density, pore size distribution, clay content and its mineralogy, hydraulic conductivity, thermal conductivity, air permeability, and penetration resistance are related to physical growing factors, and most of them can be affected by soil management and tillage.

Soil tillage is the major agricultural management practice affecting soil physical properties because it promotes changes in soil structure and porosity, which in turn affect soil hydraulic properties and the processes of water infiltration, runoff and storage, soil temperature, and chemical transport (Ahuja et al., 1998). According to these authors, soil tillage generally decrease soil bulk density and increase soil porosity by loosening up the soil. These changes are greater with the initial primary tillage (e.g., moldboard or chisel plow), but moderate by secondary tillage (e.g., disking). The magnitude of the changes varies with the nature of the soil, tillage method, and soil water content. The changes in these properties are not permanent and tend to revert asymptotically over time to values close to those of soil before tillage due to natural reconsolidation, during cycles of wetting and drying, and due to slaking and dispersion of soil aggregates enhanced by the raindrop impact at the soil surface.

In general, no-till topsoil layer has significant greater bulk density (Fernandes et al., 1983; Derpsch et al., 1991; Hubbard et al., 1994; Stone & Silveira, 2001; Bertol et al., 2004), lower saturated hydraulic conductivity (Hubbard et al., 1994), and more water than the same zone on the minimum tillage and conventional tillage treatments (Sidiras et al., 1983; Bragagnolo & Mielniczuk, 1990; Salton & Mielniczuk, 1995). At field conditions, where raindrop impact need to be considered, greater infiltration rates can be found in no-till plots compared to conventional tillage because of residues kept on the surface dissipate raindrop kinetic energy and avoid crust formation. Despite of lower total porosity, no-till system presents more pore uniformity and continuity than the conventional system, mainly because of biological porosity created by root death and soil mesofauna (Fernandes et al., 1983; Abreu et al., 2003). This kind of porosity has greater stability which, along with greater protection against raindrop impact promoted by the residues kept on the surface, can result in higher infiltration rates under natural rain at field condition (Lal, 1976; Centurion & Demattê, 1985), mainly because of avoiding crust formation (Edwards, 1982).

The arrangement of the soil particles must be such that at least 10 per cent of the soil volume is contained in pores wider than 50 µm (macropores), to allow excess water to drain freely through the soil profile and these pores must run from the surface to a depth sufficiently below the surface to allow adequate root growth in an aerobic environment (Greenland, 1979). According to this author, it is desirable also that at least 10 per cent of the soil volume is filled with pores which store water used by plant, in the range of 0.5 to 50 µm equivalent pore diameter.

The changes in pore size distribution due to tillage can be determined using the soil-water content-suction relationship, known as soil water retention curve. Based on the literature and empirical analysis of the available data on soil water retention curve, Ahuja et al. (1998) pointed out that: (a) under field conditions the tillage did not significantly change the air-entry value of the soil; (b) tillage increased the absolute value of the slope of the log-log relationship bellow the air-entry value; and (c) the changes due to tillage in the retention curve occurred only in the large pore-size range, approximately between the air-entry pressure suction value and 10 times the air-entry value.

The pore size distribution is reflected in shape of log-normal soil-water content-suction curve and the higher the volume of larger pores the higher the slope of the water retention curves below air-entry value. According to Dexter (2004), this value can be used as an index of soil physical quality (called *S* index) which is intended to be easily and unambiguously measurable using standard laboratory equipments. The value of *S* is indicative of the extent to which the soil porosity is concentrated into a narrow range of pore sizes and, in most soils, larger values of *S* are consistent with the presence of a better-defined microstructure.

Several studies were carried out to determine soil tillage effect on physical and hydrological properties but most of them showed only basic attributes (bulk density, total porosity, macro and microporosity) at a given sampling time. The objective of this study is to determine some physical attributes after 9 years of applying soil tillage and nutrient sources treatments, as well as their seasonal changes during a 12 month period, considering also changes in pore size distribution and saturated hydraulic conductivity.

1.4 Material and Methods

This study was performed using samples collected at a field experiment carried out since may 1994 at the Epagri Experimental Station of Campos Novos (Campos Novos/SC, Brazil, 27º24'S, 51º13'W, 970 m.a.s.l.) with the objective of studying long-term effects of applying soil tillage and nutrient sources treatments on soil properties and crop production. The soil is a Typic Haplorthox, a Nitossolo Vermelho in Brazilian classification (EMBRAPA, 1999), with high clay, medium organic matter, and high base saturation at soil surface (Table 1.1).

The crops were seeded in a three-year crop rotation, including crops for grain production in spring/summer season and cover crops in autumn/winter season, according to the sequence: triticale or rye/soybean/common vetch/corn/black oat/black bean .

Table 1.1 - General physical and chemical characterization of the analyzed soil profile at experimental site at the beginning of the experiment.

Horizon	Depth	Clay	Silt	Sand	OC	pH	S	T
	cm	------------------	%	-------------------			-- $cmol_c$	L^{-1} --
Ap	0 – 23	70.5	27.1	2.4	1.84	7.0	13.18	14.28
BA	23 – 38	74.5	24.2	1.3	1.55	6.4	8.65	11.95
Bt1	38 – 62	82.0	17.7	0.8	1.26	5.3	2.23	12.73
Bt2	62 – 88	82.0	17.5	0.4	0.86	5.3	1.83	10.63
Bw	88 – 134+	76.7	22.4	0.9	0.40	4.9	0.53	10.13

OC = organic carbon; S = sum of basic cations; T = cation exchange capacity at pH 7.

1.4.1 Treatments

The main treatments were a combination of residue management and soil tillage, namelly: (NT) no-till; (CP) chisel plow + 1 secondary disking; (CT) primary + 2 secondary disking; (CTb) CT wit crop residues burned; and (CTr) CT with crop residues removed from the field. They were established annually, in plots 6 m wide and 30 m long transversal to slope, before seeding of spring/summer cash crops. The chisel and the primary disking plowed respectively down to 25 and 15 cm depth. Winter cover crops were seeded in autumn using a direct drilling machine. A tractor with approximately 4.0 Mg and four-wheel drive was used to perform the primary tillage operations (i.e. primary disking and chisel plow) and a tractor with approximately 2.9 Mg and two–wheel drive was used to perform the secondary tillage operations (i.e. secondary disking) and seeding. Only soybean and triticale were harvested with a combine harvester with mass of about 10 Mg.

Nutrient sources treatments consisted of: (C) control, without nutrients application; (MF) mineral fertilizers according to official recommendation for each crop (COMISSÃO DE FERTILIDADE DO SOLO – RS/SC, 1995); (PL) 5 Mg ha^{-1} y^{-1} of wet-matter of poultry litter; (CM) 60 m^3 ha^{-1} y^{-1} of slurry cattle manure; and (SM) 40 m^3 ha^{-1} y^{-1} of slurry swine manure. Nutrient sources were applied just before the summer crops seeding in plots with 6 m wide and 30 m long, transversal to soil tillage systems (slope direction), before the secondary tillage.

The experimental design consists of a factorial 5 x 5, with 25 treatment combinations and three replications applied in randomized subdivided blocks, as shown in Appendix A.

1.4.2 Soil sampling and bulk density

Undisturbed cores were sampled in all plots at the end of ninth year (April 2003, six months after applied last tillage) at 0-5, 5-10, 12-17, and 27-32 cm layers, using stainless steel rings with 5.0 cm of height and 6.2 cm of diameter (approximately 140 cm^3 volume). Cores were sampled also at 2.5-7.5 and 12.5-17.5 cm layer before tillage operations, and at 1, 60, 120 and 240 days after seeding during the tenth year of the experiment (October/2003 to July/2004), at combinations of mineral fertilizer with all tillage systems. The cores were sampled at the crop interrow, avoiding areas of recent machinery traffic.

Bulk density (BD) was determined by the relation between particle dry-mass and total core volume, and parameters related to soil porosity were determined from soil water retention curve performed in undisturbed and disturbed samples.

1.4.3 Water retention curve parameters

The water retention curves for low tension were obtained from undisturbed samples. Soil cores were prepared removing soil excess at both edges, filter paper fixed by rubber on the bottom, and saturated by capillarity during 24 hours. After saturation, soil cores were submitted consecutively to suctions of 3, 7, 12, 22, 60 and 100 hPa, respectively for 6, 12, 24, 24, 48 and 48 hours at tension table. Mass of cores plus filter paper and rubber was determined after saturation and suctions. Control samples were used to correct water retention at rubber and filter paper. Water retention at 1000, 3000 and 15000 hPa was determined with Richards's apparatus using disturbed soil samples (diameter < 2 mm) from the same depths and times as for the cores with preserved structure.

Total porosity (TP), microporosity (Mic), and water content considered at field capacity (FC) and at permanent wilting point (PWP) values were obtained from the water retention curve and correspond, respectively, to volumetric water content at 0, 60, 100 and 15000 hPa suction. Macroporosity (Mac) and water availability capacity (WAC) correspond, respectively, to the difference in volumetric water content between TP and Mic, and between FC and PWP.

Mean values of volumetric water content for some treatments and respective suction were used to adjust them to the van Genuchten equation (van Genuchten, 1980) using RETC software (U.S. Salinity Laboratory, 1999). Pore size distribution, in classes of diameter previously defined from selected suctions, was calculated from volumetric water retention curve at each pore diameter limit between classes, using the van Genuchten equation:

$$T = T_r + \frac{(T_s - T_r)}{[1 + (a?_m)^n]^m} \qquad (1.1)$$

where T represents the volumetric water content at a given suction ($cm^3\ cm^{-3}$), T_r the residual volumetric water content ($cm^3\ cm^{-3}$), T_s the saturated volumetric water content ($cm^3\ cm^{-3}$), $?_m$ the matric potential or suction (hPa), and a , n and m the coefficients.

According to the capillary theory, suctions were determined as those necessary to remove water from soil pores with diameter wider than class limit by the equation (Flint & Flint, 2002 - modified):

$$?_m = (4\,s\,\cos ?)/D \qquad (1.2)$$

where $?_m$ represents the matric potential (hPa), s the surface tension of water (727 hPa at 20 ºC), $?$ the contact angle between liquid and solid (= 0º for soil-water contact), and D the effective diameter radius (µm).

1.4.4 Saturated hydraulic conductivity

Soil cores 7.5 cm high and 10.8 cm diameter were sampled at 1, 60 and 120 days after seeding during the tenth year of the experiment, using stainless steel rings at 1.0-8.5 and 11.0-18.5 cm layers in all soil tillage treatments of mineral fertilizers nutrient source to determine saturated hydraulic conductivity. To perform this determination, plastic rings 5 cm high and 10.8 cm internal diameter were installed in upper edge of stainless steel ring and fixed with adhesive tape in order to prevent water loss. Plastic rings had a pipe connection to supply water individually to each sample. In order to maintain constant water head of 4 cm above the soil core, water was supplied from a box with constant head (constant head infiltrometer) with level regulated by a floating device.

Soil cores were saturated by capillarity for 24 hours, positioned on the device and allowed to infiltrate water for 6 hours previously to determinations, in order to reach constant percolation rate. After this time, three replications of percolated water were sampled in 10 minutes time interval and calculation of saturated hydraulic conductivity was performed using the equation (Reynolds & Elrick, 2002):

$$K_s = 4V_wL/[pd_c^2 ? t(h+L)] \qquad (1.3)$$

where K_s represents the saturated soil hydraulic conductivity (cm h^{-1}), V_w the water volume (cm^3) sampled at time interval $?t$ (h), d_c the sample diameter (cm), L the sample length (cm), and h the water head at sample top (cm).

1.4.5 Statistical analysis

Treatment effects were tested by ANOVA, and differences were compared by the Tukey test ($P < 0.05$), using Statistical Analysis System software (SAS, 1989).

1.5 Results and discussion

Analysis of variance showed statistical differences for soil depth and interaction between depth and soil tillage (Table 1.2) for all soil physical and hydraulic parameters determined at the end of ninth year of soil tillage and nutrient sources treatments. There were no differences among nutrient sources and interaction between this source of variation and soil tillage and depth. The coefficient of variation was bellow 10% for most of the parameters, except for macroporosity and water availability, which are affected by the high variability usually found in larger pores determinations (Souza et al., 2001). Because of the interaction between soil depth and soil tillage, Tukey test was performed both comparing soil tillage means within each depth and comparing soil depth means within each soil tillage system.

Table 1.2 - Analysis of variance (ANOVA) for physical-hydraulic properties determined at four depths after nine years of applying five soil tillage systems and five nutrient sources.

Sources of variation	Physical-hydraulic parameters						
	BD	TP	Mac	Mic	FC	PWP	WAC
Soil tillage (ST)	ns	ns	ns	ns	ns	ns	ns
Nutrient source (NS)	ns	ns	ns	ns	ns	ns	ns
ST x NS	ns	ns	ns	ns	ns	ns	ns
Depth	***	***	***	***	***	***	***
Depth x ST	*	*	***	***	***	**	***
Depth x NS	ns	ns	ns	ns	ns	ns	ns
CV%	5.6	4.9	36.9	5.9	6.0	5.8	14.8

BD = bulk density; TP = total porosity; Mac = macroporosity; Mic = microposority; FC = field capacity; PWP = permanent wilting point; and WAC = water availability capacity.
***, **, * ,and ns = respectively statistical significance at 0.1, 1 and 5% level, and not significant.

Statistical significances were found for all soil parameters among sampling times, soil tillage (except PWP), depth (except WAC) and interaction between soil tillage and depth (except TP), and, for some parameters, interaction between depth and sampling times (Table 1.3). In order to use uniform criteria, the Tukey test was performed for all parameters comparing soil tillage and sampling time within each depth.

1.5.1 Bulk density and porosity

Statistical significance in bulk density among soil tillage was observed only at 12-17 cm layer, showing little effect of soil tillage on this parameter at that sampling time (Table 1.4). At this layer, no-till and chisel plow treatments showed lower bulk density then conventional tillage treatments. The small differences among tillage treatments at the upper layers (0-5 and 5-10 cm) are probably due to the low water content at sampling time and soil disturbance caused by direct drilling machine used to seed winter cover crops 15 days before soil sampling. The double disk system of direct drilling machine penetrated the soil down to 7-8 cm depth and, although sampling was performed at interrow area, the distance between two rows (17 cm) was too small to avoid soil disturbance, specially at surface layer (0-5 cm).

Table 1.3 - Analysis of variance (ANOVA) for physical-hydraulic properties determined at two depths (2.5-7.5 and 12.5-17.5 cm) at five sampling times during the tenth year of applying five soil tillage systems and mineral nutrient source.

Sources of variation	Physical-hydraulic parameters						
	BD	TP	Mac	Mic	FC	PWP	WAC
Soil tillage (ST)	***	*	***	***	***	ns	**
Sampling time	***	***	***	***	***	***	***
ST x Sampling time	ns	ns	ns	ns	ns	ns	ns
Depth	***	***	***	***	***	***	ns
Depth x ST	*	ns	***	***	***	**	***
Depth x Sampling time	ns	*	ns	*	ns	ns	***
CV%	6.9	5.2	33.3	6.9	7.2	7.3	15.2

BD = bulk density; TP = total porosity; Mac = macroporosity; Mic = microposority; FC = field capacity; PWP = permanent wilting point; and WAC = water availability capacity.
***, **, * , and ns = respectively statistical significance at 0.1, 1 and 5% level, and not significant.

These results are in disagreement with most previous studies (Fernandes at al., 1983; Derpsch et al., 1991; Hubbard et al., 1994; Stone & Silveira, 2001; Bertol et al., 2004), but similar results were found by Abreu (2003) and Albuquerque et al. (1995), and can be explained by the seasonal variability of bulk density, as can be observed at Table 1.5. A trend of bulk density increase was observed from the seeding time to time immediately before plowing at both depths, mainly because of reduction in total porosity in tilled treatments due to natural soil settlement caused by wetting and drying cycles, and surface breakdown of soil aggregates promoted by raindrop impact on soil surface without protection (Ahuja et al., 1998). Considering the five sampling times, no-till system showed greater bulk density then the other tillage systems at the upper layer (Table 1.6).

The greatest soil bulk density was observed at 5-10 cm layer in all soil tillage systems, followed by 12-17 cm layer. The upper (0-5 cm) and lower (27-32 cm) layers showed lower bulk density, and similar between them. Thus, the compacted layer was observed at the same depth and near the same intensity in all soil tillage treatments at that sampling time.

Table 1.4 – Physical and hydraulic properties determined at four depths after nine years of applying five soil tillage systems (averaged across nutrient sources).

Depth (cm)	Soil tillage system NT	CP	CT	CTb	CTr
	Bulk density – BD (g cm^{-3})				
0 – 5	1.10 a C	1.09 a C	1.03 a C	1.07 a B	1.08 a B
5 – 10	1.28 a A	1.27 a A	1.30 a A	1.27 a A	1.29 a A
12 – 17	1.19 b B	1.20 b B	1.26 a A	1.24 ab A	1.23 ab A
27 – 32	1.11 a C	1.11 a C	1.10 a B	1.09 a B	1.10 a B
	Total porosity – TP (cm^3 cm^{-3})				
0 – 5	0.60 a A	0.59 a A	0.61 a A	0.59 a A	0.59 a A
5 – 10	0.53 a C	0.54 a C	0.53 a B	0.53 a B	0.53 a C
12 – 17	0.56 ab B	0.57 a AB	0.54 b B	0.54 b B	0.55 b B
27 – 32	0.54 a BC	0.55 a BC	0.54 a B	0.55 a B	0.54 a BC
	Macroporosity – Mac (cm^3 cm^{-3})				
0 – 5	0.15 b A	0.19 ab A	0.22 a A	0.20 ab A	0.20 ab A
5 – 10	0.07 a B	0.07 a C	0.05 a B	0.06 a B	0.06 a B
12 – 17	0.10 a B	0.12 a B	0.07 b B	0.05 b B	0.06 b B
27 – 32	0.07 a B	0.07 a C	0.07 a B	0.08 a B	0.07 a B
	Microporosity – Mic (cm^3 cm^{-3})				
0 – 5	0.45 a A	0.40 b C	0.39 b B	0.38 b B	0.39 b B
5 – 10	0.45 b A	0.47 a AB	0.47 a A	0.47 a A	0.47 a A
12 – 17	0.46 b A	0.46 b B	0.47 ab A	0.48 a A	0.49 a A
27 – 32	0.47 a A	0.48 a A	0.47 a A	0.47 a A	0.47 a A
	Volumetric water content at field capacity – FC (cm^3 cm^{-3})				
0 – 5	0.45 a A	0.39 b C	0.38 b B	0.38 b B	0.38 b B
5 – 10	0.44 b A	0.47 a A	0.47 a A	0.47 a A	0.46 a A
12 – 17	0.44 b A	0.44 b B	0.46 ab A	0.47 a A	0.48 a A
27 – 32	0.46 a A	0.47 a A	0.46 a A	0.46 a A	0.46 a A
	Volumetric water content at permanent wilting point – PWP (cm^3 cm^{-3})				
0 – 5	0.24 a C	0.24 a C	0.23 a C	0.24 a D	0.24 a C
5 – 10	0.29 a A	0.29 a A	0.30 a A	0.29 a B	0.30 a C
12 – 17	0.29 c A	0.29 bc A	0.31 a A	0.31 a A	0.30 ab A
27 – 32	0.27 a B	0.27 a B	0.27 a B	0.27 a C	0.27 a B
	Volumetric water available capacity – WAC (cm^3 cm^{-3})				
0 – 5	0.20 a A	0.15 b BC	0.15 b B	0.14 b C	0.14 b C
5 – 10	0.15 b B	0.17 a AB	0.17 a AB	0.17 a B	0.16 ab BC
12 – 17	0.15 a B	0.15 a C	0.15 a B	0.15 a BC	0.17 a AB
27 – 32	0.19 a A	0.20 a A	0.19 a A	0.19 a A	0.19 a A

NT = no-till; CP = chisel plow; CT = conventional tillage; CTb = CT with crop residues burned; and CTr = CT with crop residues removed.

Means followed by the same small letter at a given row and capital letter at a given column are not statistically different (Tukey, $P< 0.05$).

Table 1.5 - Physical-hydraulic properties determined at two depths at five sampling times performed during the tenth year (averaged across tillage systems).

Depth (cm) and Sampling time (DAS)	Physical-hydraulic parameters						
	BD	TP	Mac	Mic	FC	PWP	WAC
	g cm^{-3}	------	------	cm^3 cm^{-3}	------	------	------
2.5 – 7.5 cm							
1	1.05 BC	0.66 A	0.20 A	0.46 A	0.44 A	0.23 B	0.21 A
60	1.00 C	0.60 B	0.23 A	0.37 C	0.34 C	0.22 B	0.12 C
120	1.04 BC	0.58 B	0.22 A	0.36 C	0.33 C	0.23 B	0.10 D
240	1.09 B	0.59 B	0.19 A	0.41 B	0.39 C	0.24 B	0.15 B
360	1.18 A	0.53 C	0.12 B	0.42 B	0.39 B	0.26 A	0.13 BC
12.5 – 17.5 cm							
1	1.15 B	0.61 A	0.12 AB	0.49 A	0.48 A	0.28 B	0.20 A
60	1.18 B	0.56 B	0.13 AB	0.43 B	0.41 B	0.29 B	0.12 C
120	1.17 B	0.55 B	0.14 A	0.41 B	0.39 B	0.29 B	0.10 CD
240	1.20 B	0.56 B	0.09 B	0.48 A	0.46 A	0.30 B	0.16 B
360	1.30 A	0.51 C	0.08 B	0.43 B	0.41 B	0.32 A	0.09 D

DAS = days after seeding; BD = bulk density; TP = total porosity; Mac = macroporosity; Mic = microposority; FC = field capacity; PWP = permanent wilting point; and WAC = water available capacity.
Means followed by the same letters at a given column for each depth are not statistically different (Tukey, P< 0.05).

Table 1.6 - Physical-hydraulic properties determined at two depths of five tillage systems (averaged across sampling times performed during the tenth year).

Depth (cm) and Tillage system	Physical-hydraulic parameters						
	BD	TP	Mac	Mic	FC	PWP	WAC
	g cm^{-3}	------	------	cm^3 cm^{-3}	------	------	------
2.5 – 7.5 cm							
No-till	1.16 A	0.57 B	0.12 B	0.44 A	0.42 A	0.26 A	0.18 A
Chisel plow	1.02 B	0.60 A	0.22 A	0.39 B	0.36 B	0.22 B	0.14 B
Conventional tillage	1.08 AB	0.59 AB	0.19 A	0.40 B	0.38 B	0.24 AB	0.14 B
CT + residue burned	1.03 B	0.60 A	0.23 A	0.38 B	0.35 B	0.23 B	0.12 B
CT + residue removed	1.07 B	0.59 AB	0.20 A	0.39 B	0.37 B	0.24 AB	0.13 B
12.5 – 17.5 cm							
No-till	1.21 A	0.56 A	0.12 A	0.44 A	0.42 A	0.29 A	0.13 A
Chisel plow	1.19 A	0.57 A	0.13 A	0.44 A	0.42 A	0.30 A	0.12 A
Conventional tillage	1.22 A	0.55 A	0.10 A	0.45 A	0.44 A	0.30 A	0.14 A
CT + residue burned	1.18 A	0.56 A	0.11 A	0.45 A	0.43 A	0.29 A	0.14 A
CT + residue removed	1.20 A	0.56 A	0.09 A	0.46 A	0.44 A	0.30 A	0.14 A

BD = bulk density; TP = total porosity; Mac = macroporosity; Mic = microposority; FC = field capacity; PWP = permanent wilting point; and WAC = water available capacity.
Means followed by the same letter at a given column for each depth are not statistically different (Tukey, P< 0.05).

Total porosity, estimated by volumetric water retention at saturation, showed the same trend as bulk density when considering soil tillage systems. At 12-17 cm layer, total porosity was higher for chisel plow and no-till systems (Table 1.4). At 2.5-7.5 cm layer, considering the five sampling times, total porosity was lower in no-till system (Table 1.6). Total porosity reduced significantly from the first to the last sampling time in both depths (Table 1.5 and Figure 1.1), following the asymptotic trend to reach the same porosity as before tillage. Despite the high coefficient of variation found for macroporosity, statistical differences were found after 9 years of applying soil tillage treatments at 0-5 cm layer (Table 1.4) and at 2.5-7.5 cm layer when considering five sampling times (Table 1.6), where macroporosity was lower for no-till treatments. Except for chisel plow, there were differences only between the upper layers (0-5 cm) as compared to the others (Table 1.4). Contrary to soil bulk density behavior, macroporosity showed a trend to decrease over time after plowing and seeding, due to natural soil reconsolidation, since no external stress was applied during the sampling period (Table 1.5 and Figure 1.1). Macroporosiy was lower than 10% at 5-10 cm and 27-32 cm layers in NT and CP treatments, and below 5 cm depth in CT treatments, showing restrictive values to good internal water and gas flux as well as for root elongation.

Differences in microporosity were observed at the three upper layers sampled after 9 years of applying soil tillage systems. It was higher at 0-5 cm and lower at 5-10 and 12-17 cm layers for no-till system as compared to others tillage systems. Considering absolute values, we could pointed out that microporosity was affected only at upper layer (0-5 cm after nine years and 2.5-7.5 cm during the tenth year), where lower values were found in tilled treatments. In NT system, there were no differences in microporosity among depths, while chisel plow and conventional tillage systems showed lower microporosity at 0-5 cm layer, where higher total porosity and macroporosity were found. Microporosity did not show a trend of change in increasing sampling times after seeding (Figure 1.1) and seems to be more susceptible to the environmental conditions at the sampling time than a function of time after plowing and seeding. Volumetric water content at field capacity showed the same trend as microporosity because of the small difference between them at applied suction (respectively 100 hPa and 60 hPa).

Since the volumetric water content at permanent wilting point is a parameter that show little variation over time because it is affected by intrinsic soil properties (mainly clay content and type of clay mineral and stable organic matter), variation in volumetric water content at permanent wilting point is related to variation in bulk density. Volumetric water content at permanent wilting point showed smaller variation among soil tillage systems, both at different depths (Table 1.4) and sampling times (Table 1.5), and greater differences among depths (Table 1.4). The water available capacity was higher in no-till system at upper layer (0-5 cm in April 2003 and 2.5-7.5 cm for five sampling times) and lower at 5-10 cm layer (Table 1.4), mainly because of variation in macroporosity. High variation in volumetric water available capacity was observed at different sampling times (Table 1.5).

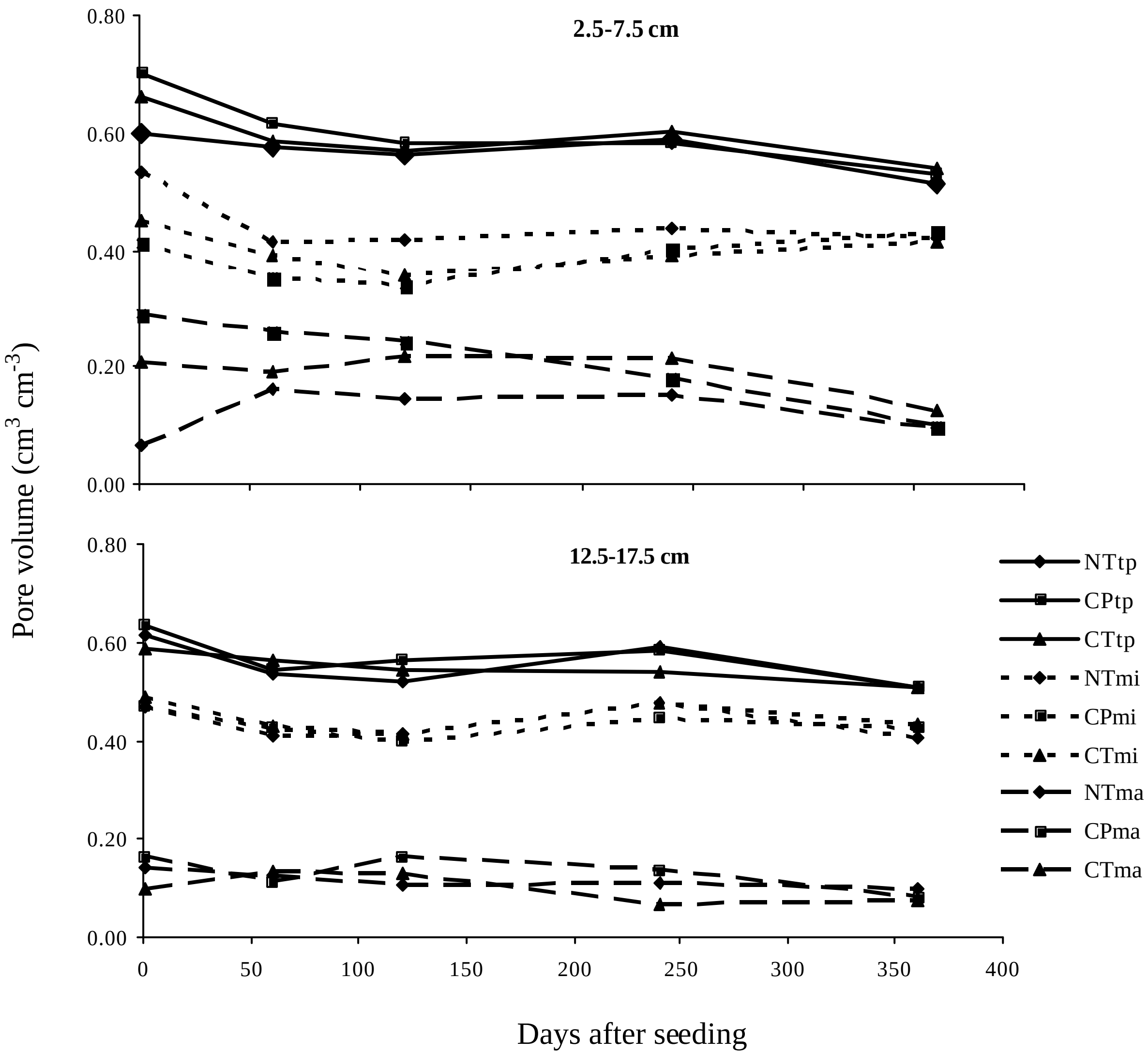

Figure 1.1 – Changes in pore size distribution during the tenth year in no-till (NT), chisel plow (CP), and conventional tillage (CT) treatments. (tp = total porosity, mi = microporosity, and ma = macroporosity).

1.5.2 Pore size distribution

Measured points of water retention curves and theirs respective van Genuchten adjustments, as well as pore size distribution for three soil tillage systems and four depths are showed at Figure 1.2. Air-entry values were lower at 0-5 cm and higher at 5-10 cm layer because of higher volume of macropores at first and lower at second layer. No-till and chisel plow showed the same trend in pore size distribution at four depths, with higher volume of larger pores (> 50 µm) at 0-5 cm and 12-17 cm layers, and greater volume of fine pores at 5-10 and 27-32 cm layers (Figure 1.2). Conventional tillage showed high differentiation in pore size distribution at surface (0-5 cm layer) as compared to others. Smaller volume of larger pores at 12-17 cm for conventional tillage as compared to no-till and chisel plow is due to the plow pan layer, with greater bulk density and smaller macroporosity, formed at this treatment as a result of primary disking operation, when one rear tyre drives in the bottom of the plowing depth.

Considering the physical index S for evaluating soil physical quality proposed by Dexter (2004), the best soil quality was found at 0-5 cm layer for all tillage treatments followed by 12-17 cm layer in chisel plow and no-till treatments. For others combinations of soil tillage and depths, the slope of water retention curve bellow air-entry value were smaller, showing worst pore size distribution, with lower volume of larger pores.

Pore size distribution changed seasonally, especially at the upper 2.5-7.5 cm layer (Table 1.5 and Figure 1.1). Total porosity showed differences among tillage systems only immediately after sowing and was higher for CP, intermediate for CT and lower for NT system. In NT system, lowest volume of macropores (> 50 µm) was found immediately after seeding, greater volume from 60 to 240 days after seeding and intermediate before next seeding. Greater volume of micropores (< 50 µm diameter) was found in no-till system immediately after seeding operations, and differences reduced over time.

For chisel plow system there was a trend of reducing larger pores over time after plowing, but it did not result in increasing volume of fine pores. For this tillage system, lower volume of larger pores was found only 360 days after plowing and sowing operations (immediately before subsequent annual tillage). These results confirm that tillage operations increase macroporosity and total porosity, but this effect is reduced over time and tend asymptotically to values equal or smaller than as before tillage.

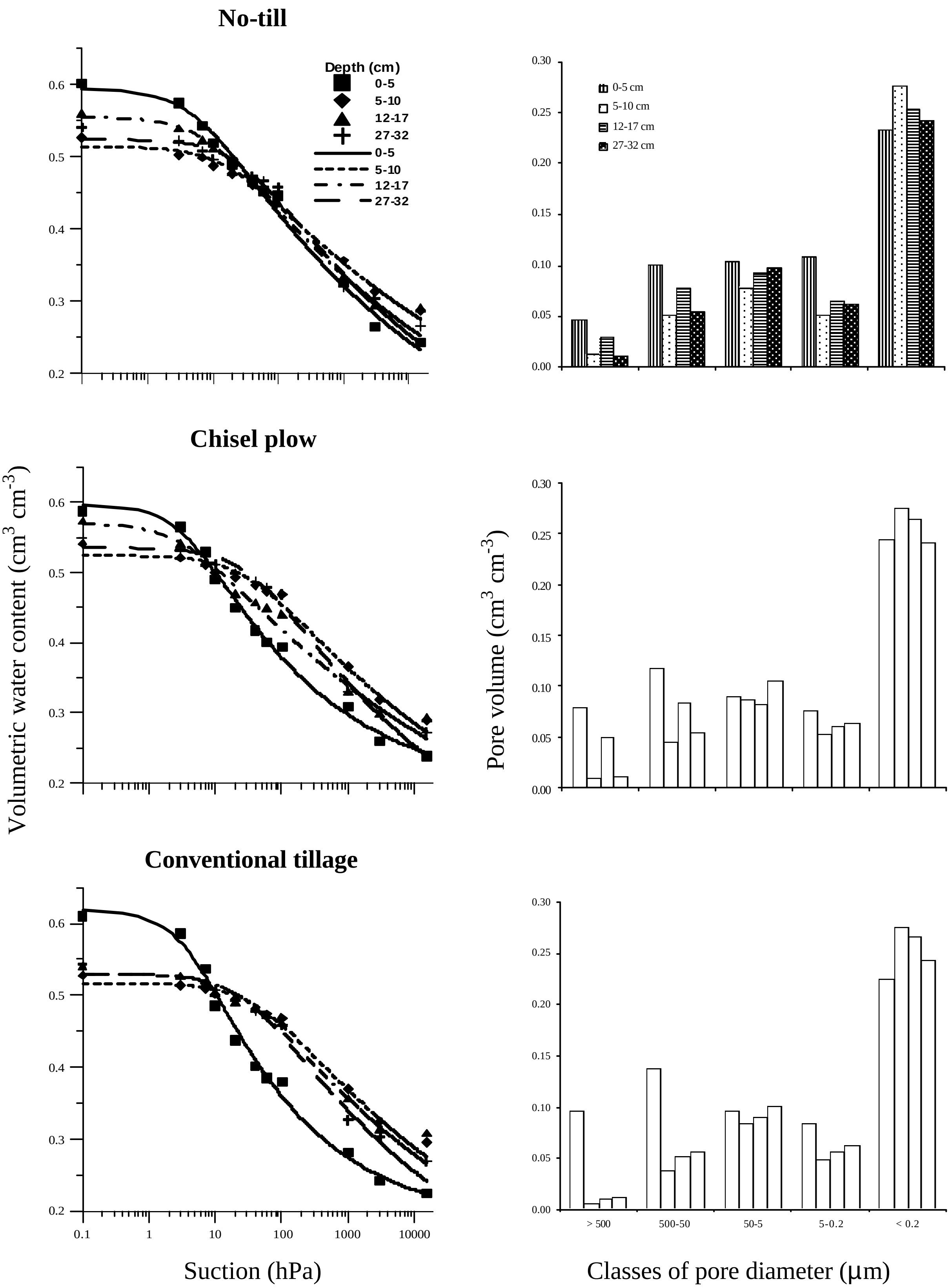

Figure 1.2 - Soil water retention curves and pore size distribution at four depths, after nine years of applying no-till, chisel plow and conventional tillage (average across nutrient sources).

1.5.3 Saturated hydraulic conductivity

The smallest saturated hydraulic conductivity was found at 1.0-8.5 cm layer in no-till system, and no differences were found among others tillage systems at the same depth and among all tillage systems at 11.0-18.5 cm layer (Table 1.7). Saturated hydraulic conductivity was greater at 1.0-8.5 cm as compared with 11.0-18.5 cm layer for all tillage systems. There were no differences in saturated hydraulic conductivity among sampling times. Lower soil saturated hydraulic conductivity at upper layer of no-till system is associated to lower macroporosity found at this layer at those sampling times, since there was a significant correlation between these two parameters (Figure 1.3). The pore continuity, if present, was not enough to increase the saturated hydraulic conductivity in order to compensate for the lesser amount of large pores found for this soil tillage system.

Table 1.7 - Soil saturated hydraulic conductivity at two depths and three sampling times performed during the tenth year of applying five soil tillage systems and mineral fertilizer nutrient source.

Depth (cm)	Sampling time (DAS)	Soil tillage system				
		NT	CP	CT	CTb	CTr
		--- $cm\,h^{-1}$ ---				
1.0 – 8.5	1	2.5	28.7	23.5	24.3	23.8
	60	9.0	26.6	16.6	20.7	38.8
	120	9.1	17.8	21.2	18.7	14.3
	Average	6.9 b A	24.4 a A	20.4 ab A	21.2 a A	25.6 a A
11.0 – 18.5	1	2.2	4.3	6.1	2.0	0.1
	60	4.1	3.8	3.8	3.6	2.5
	120	3.0	4.8	4.7	4.4	3.2
	Average	3.1 a B	4.3 a B	4.9 a B	3.3 a B	2.0 a B

DAS = days after seeding; NT = no-till; CP = chisel plow; CT = conventional tillage; CTb = CT with crop residues burned; and CTr = CT with crop residues removed.

Means followed by the same small letter at a given row and capital letter at a given column are not statistically different (Tukey, $P < 0.05$).

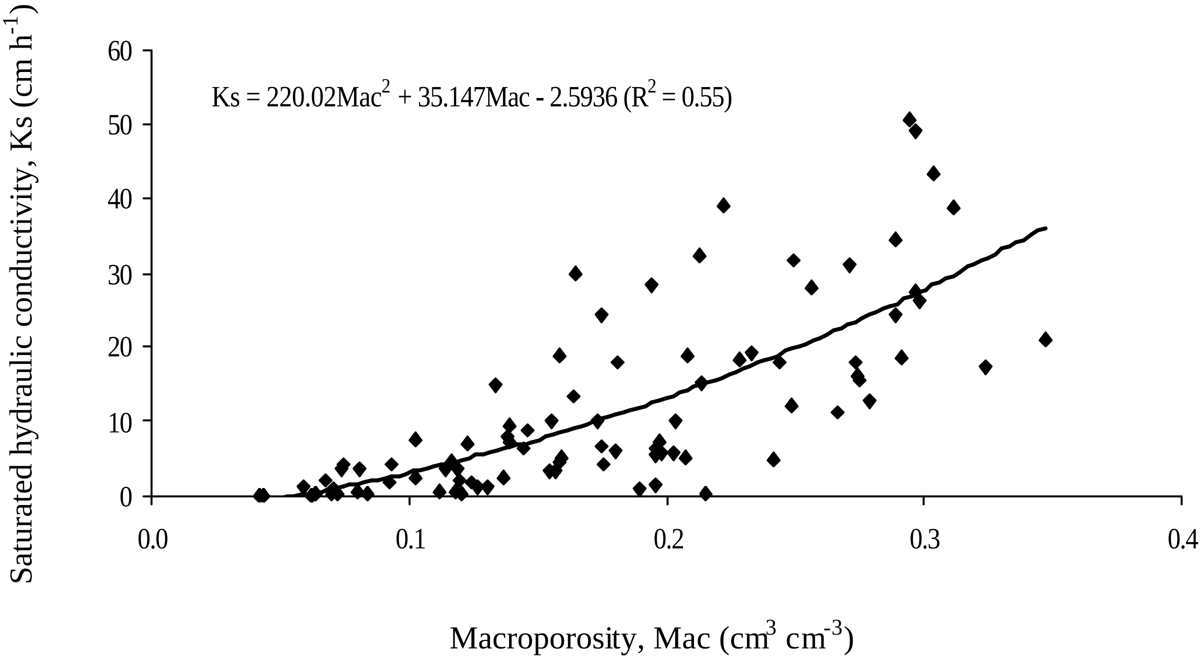

Figure 1.3 – Correlation between macroporosity (Mac) and saturated hydraulic conductivity (Ks) for core samples collected at two depths and three sampling times during the corn cycle.

1.6 Conclusions

Soil physical and hydraulic properties were tillage and time dependent. Tilled treatments increased total porosity and macroporosity and reduced bulk density in the surface layer, but this effect reduced over time due to natural soil reconsolidation.

All tillage treatments showed greater bulk density at intermediate layers and reduced down to deeper layers, indicating the presence of compacted layer at depth around 5-20 cm.

Soil saturated hydraulic conductivity was lower at 1.0-8.5 cm layer of no-till system, and no differences were found at 11.0-18.5 cm layer.

Nutrient sources treatments did not affect soil physical and hydraulic properties.

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CAPITULO 2. ESTABILIDADE DE AGREGADOS APÓS CURTO E LONGO PRAZO DE APLICAÇÃO DE SISTEMAS DE MANEJO DO SOLO E DE FONTES DE NUTRIENTES, EM UM NITOSSOLO VERMELHO.

2.1 Resumo

O solo deveria ter uma estrutura com alta qualidade e estabilidade para ser usado em agricultura. A capacidade do solo em manter sua estrutura contra a ação de agentes erosivos, como por exemplo a água, é geralmente alta em condições naturais e reduz quando o solo é submetido ao preparo freqüente e intensivo. O uso de sistemas conservacionistas de preparo pode resultar em recuperação da qualidade e estabilidade da estrutura do solo. O efeito de curto e de longo prazo de cinco sistemas de preparo do solo (PD = plantio direto; PE = escarificação + gradagem; PC = aração + 2 gradagens; PCq = PC com resíduos queimados e; PCr = PC com resíduos retirados) associados com cinco fontes de nutrientes (T = testemunha; AM = adubação mineral de acordo com a recomendação para manutenção de cada cultura; EA = 5 Mg ha^{-1} a^{-1} de cama de aviário, base úmida; EB = 60 m^3 ha^{-1} a^{-1} de esterco líquido de bovinos e; 40 m^3 ha^{-1} a^{-1} de esterco líquido de suínos) sobre a estabilidade dos agregados foi determinada ao final do nono ano de experimentação (quatro profundidades) e em cinco épocas de amostragens efetuadas durante o décimo ano, em um Nitossolo Vermelho com alto conteúdo de argila, no Sul do Brasil. A distribuição de tamanho de agregados secos ao ar foi fortemente afetada pela densidade do solo e maiores valores de diâmetro médio geométrico (DMG_{SA}) encontrados em alguns sistemas de preparo ou profundidades podem ser parcialmente devidos ao maior estado de compactação do solo. Depois de nove anos o PD e o PE apresentaram maior DMG_{SA} na camada superficial devido ao maior conteúdo de matéria orgânica bem como à menor mobilização do solo comparado aos sistemas de preparo convencional (PC, PCq e PCr). A estabilidade dos agregados em água, por outro lado, foi afetada pelo teor de água nas amostras por ocasião da realização do teste, resultando em alto coeficiente de variação desta determinação. O PD apresentou maior diâmetro médio geométrico dos agregados estáveis em água (DMG_{EA}) na camada de 0-5 cm, o PC nas camadas de 5-10 e 12-17 cm e o PE valores intermediários entre o PD e o PC. O índice de estabilidade dos agregados (IE_{DMG}) na camada superficial foi maior nos tratamentos onde os resíduos das culturas foram mantidos na lavoura (PD, PE e PC) e não foram encontradas diferenças na camada de 27-32 cm. As fontes de nutrientes apresentaram pequeno efeito sobre o DMG_{SA} e DMG_{EA} e nenhum efeito sobre o IE_{DMG}.

Palavras chaves: preparo do solo, estabilidade de agregados, estercos.

AGGREGATE STABILITY AS AFFECTED BY SHORT AND LONG-TERM TILLAGE SYSTEMS AND NUTRIENT SOURCES ON A HAPLORTHOX IN SOUTHERN BRAZIL

2.2 Abstract

A soil should have a structure with high quality and stability in order to be used in agriculture. The ability of the soil to maintain its structure against the action of water is usually high in natural conditions and decrease when the field is subjected to frequent and intensive cultivation. The effect of five soil tillage systems (NT = no-till; CP = chisel plow + 1 secondary disking; CT = primary + 2 secondary disking; CTb = CT with crop residues burned; and CTr = CT with crop residues removed from the field) associated with five nutrient sources (C = control, without nutrient application; MF = mineral fertilizers according official recommendation for each crop; PL = 5 Mg ha^{-1} y^{-1} of wet-matter of poultry litter; CM = 60 m^3 ha^{-1} y^{-1} of slurry cattle manure; and SM = 40 m^3 ha^{-1} y^{-1} of slurry swine manure) on wet-aggregate stability was determined after nine years (four depths) and in five sampling times during the tenth year (two depths) of the experiment. Size distribution of air-dry aggregates was strongly affected by its bulk density and greater values of geometric mean diameter (GMD_{AD}) found in some soil tillage or depths can be due partly to the greater compaction degree. After nine years, NT and CP showed greater GMD_{AD} due to the higher organic matter content as well as because lesser soil mobilization by soil tillage compared to conventional systems (CT, CTb, and CTr). Aggregate stability in water, on the other hand, was affected by antecedent gravimetric water content of aggregates and resulted in high coefficient of variation of this determination. NT system showed greater geometric mean diameter of water stable aggregates (GMD_{WS}) at 0-5 cm layer, CT at 5-10 and 12-17 cm layer, and CP intermediate values in between NT and CT. Stability index (SI_{GMD}) at the upper layer was greater in treatments where crop residues were kept in the field (NT, CP and CT) and no differences were found at 27-32 cm layer. Nutrient sources showed little effect on GMD_{AD} and GMD_{WS} and no effect on SI_{GMD}.

Keywords: Soil tillage, aggregate stability, manure.

2.3 Introduction

Soil structure has been defined as the size, shape and arrangement of the solid particles and voids, and is highly variable and associated with a complex set of interactions among mineralogical, chemical and biological factors (Letey, 1991). Although soil structure is not considered as a factor directly related to crop production, it play an important role in water and air supply to roots, root elongation, nutrient availability, and macrofauna development. Good structure for plant growth can be defined in terms of the presence of pores for the storage of water available to plants, pores for the transmission of water and air, and pores in which roots can grow (Oades, 1984).

For use in agriculture or horticulture, a soil must have not only a good structure, but also a structure which will persist for a long time, e.g., a structure with high quality and stability (Dexter, 1988). This author classify structure stability in two principal types: (a) the ability of the soil to maintain its structure under action of water; and (b) the ability of drier (moist) soil to maintain its structure under the action of external mechanical stresses. The first type of structure stability is commonly evaluated through wet-sieving methods to determine aggregate stability in water, as proposed by Yoder (1936) and Kemper & Chepil (1965). The evaluation of structure stability against external stresses can be determined using compressibility test (Gupta et al., 2002) and shear test (Fredlung & Vanapalli, 2002).

The best soil structure is found usually in natural conditions, and most soils in the field when subjected to frequent and intensive cultivation, suffer deterioration in its structure which reflects by a decrease in aggregate stability (Da Ros et al., 1997; Silva & Mielniczuk, 1997; Carpenedo & Mielniczuk, 1990; D’Andréa et al., 2002). Among tillage systems, no-till usually show greater aggregate stability than conventional tillage at upper layer (Hamblin, 1980; Carpenedo & Mielniczuk, 1990; Campos et al., 1995; Castro Filho et al., 1998; Beutler et al., 2001; D’Andréa et al., 2002), but in both tillage systems soil aggregates were compacted, with predominance of micropores (Carpenedo & Mielniczuk, 1990).

Decrease in aggregate stability from natural conditions to intensive cultivation and increase of this parameter with introduction of conservation soil tillage are usually associated with variation in carbon content in soil (Campos et al., 1995; Silva & Mielniczuk, 1997; Castro Filho et al., 1998; Beutler et al., 2001; D’Andréa et al., 2002). Both macro and microaggregates (> and < 250 μm, respectively) depend on organic matter for stability against disruptive forces caused by rapid wetting (Oades, 1984). According to Tisdall & Oades

(1982), the organic binding agents are classified into transient (mainly polysaccharides), temporary (roots and fungal hyphae), and persistent (resistant aromatic components associated with polyvalent metal cations and strongly sorbed polymers). Since roots and hyphae stabilize macroaggregates and soil tillage influences the growth of plant roots and the oxidation of organic carbon, macroaggregation is mainly controlled by soil management and tillage (Tisdall & Oades, 1982; Oades, 1984) and can show seasonal variation. On the other hand, water-stability of microaggregates depends on the persistent organic binding agents and appears to be a characteristic of the soil, less variable over time (Tisdall & Oades, 1982).

Crops have root systems with different ability in promoting aggregation and stabilization of soil aggregates due to mechanical effect (Tisdall & Oades, 1979; Campos et al., 1999; Silva & Mielniczuk, 1997 and 1998), exudates production, or mychorrizal association (Tisdall & Oades, 1979; Tisdall, 1991; Degens, 1997) and can contribute to seasonal variation of aggregate stability over a growing season (Campos et al., 1999).

Studies of aggregate stability in different tillage systems usually were done at a specific time and not necessarily reflect the entire effect during the cropping season. Furthermore, scarce studies are available about annually manure applications in doses recommended only for nutrient supply and their interactions with soil tillage. This study was performed with the objective to study the long-term and seasonal effect of soil tillage systems and nutrient sources on aggregate stability, and correlations of aggregate stability with some soil physical and chemical attributes.

2.4 Material and Methods

This study was performed using samples collected at a field experiment carried out since may 1994 at Epagri Experimental Station of Campos Novos (Campos Novos/SC, Brazil, 27º24’S, 51º13’W, 970 m.a.s.l.) with the objective of studying long-term effects of applying soil tillage and nutrient sources treatments on soil properties and crop production. The soil is a Typic Haplorthox, a Nitossolo Vermelho in Brazilian classification (EMBRAPA, 1999), with high clay, medium organic matter, and high base saturation at soil surface (Table 2.1).

The crops were seeded in a three-year crop rotation, including crops for grain production in spring/summer season and cover crops in autumn/winter season, according to the sequence: triticale or rye/soybean/common vetch/corn/black oat/black bean.

Table 2.1 - General physical and chemical characterization of the analyzed soil profile at experimental site at the beginning of the experiment.

Horizon	Depth	Clay	Silt	Sand	OC	pH	S	T
	cm	-------------------	%	-------------------			-- $cmol_c\ L^{-1}$ --	
Ap	0 – 23	70.5	27.1	2.4	1.84	7.0	13.18	14.28
BA	23 – 38	74.5	24.2	1.3	1.55	6.4	8.65	11.95
Bt1	38 – 62	82.0	17.7	0.8	1.26	5.3	2.23	12.73
Bt2	62 – 88	82.0	17.5	0.4	0.86	5.3	1.83	10.63
Bw	88 – 134+	76.7	22.4	0.9	0.40	4.9	0.53	10.13

OC = organic carbon; S = sum of basic cations; T = cation exchange capacity at pH 7.

2.4.1 Treatments

The main treatments were a combination of residue management and soil tillage, namelly: (NT) no-till; (CP) chisel plow + 1 secondary disking; (CT) primary + 2 secondary disking; (CTb) CT wit crop residues burned; and (CTr) CT with crop residues removed from the field. They were established annually in plots 6 m wide and 30 m long, transversal to slope, before seeding of spring/summer cash crops. The chisel and the primary disking plowed the soil respectively down to 25 and 15 cm depth. Winter cover crops were seeded in autumn using a direct drilling machine. A tractor with approximately 4.0 Mg and four-wheel drive was used to perform the primary tillage operations (i.e. primary disking and chisel plow) and a tractor with approximately 2.9 Mg and two–wheel drive was used to perform the secondary tillage operations (i.e. secondary disking) and seeding. Only soybean and triticale were harvested with a combine harvester with mass of about 10 Mg.

Nutrient sources treatments consisted of: (C) control, without nutrients application; (MF) mineral fertilizers according official recommendation for each crop (COMISSÃO DE FERTILIDADE DO SOLO – RS/SC, 1995); (PL) 5 Mg ha^{-1} y^{-1} of wet-matter of poultry litter; (CM) 60 m^3 ha^{-1} y^{-1} of slurry cattle manure; and (SM) 40 m^3 ha^{-1} y^{-1} of slurry swine manure. Nutrient sources were applied just before the spring/summer crops seeding, in plots with 6 m wide and 30 m long, transversal to soil tillage systems (slope direction), before the secondary tillage.

The experimental design consists of a factorial 5 x 5, with 25 treatment combinations and three replications applied in randomized subdivided blocks, as shown in Appendix A.

2.4.2 Soil sampling

Undisturbed cores were sampled in all plots at the end of ninth year (April 2003, six months after applied last tillage) at 0-5, 5-10, 12-17, and 27-32 cm layers, using stainless steel rings with 5.0 cm of height and 6.2 cm of diameter (approximately 140 cm^3 volume). Cores were sampled also at 2.5-7.5 and 12.5-17.5 cm layers before tillage operations, and at 1, 60, 120 and 240 days after seeding during the tenth year of the trial (October/2003 to July/2004), at combinations of mineral fertilizer with all tillage systems. The cores were sampled at the crop interrow, avoiding area of recent machinery traffic.

Aggregate stability was determined from the same cores used for water retention curve determination at tension table. After application of 100 hPa suction, part of the sample was used to determine water content and the remaining was carefully broken down to clods less than 8 mm diameter which passed by a screen with that opening. The clods/aggregates were allowed to dry for 72 hours at laboratory conditions and placed inside metal cans with lid, but without hermetic closing, where they remained until aggregate stability test was performed. These aggregates are named "air-dry aggregates".

2.4.3 Air-dry aggregate size distribution

Air-dry aggregates (AD) were spread carefully on a plastic box using right-and-left movements, starting at one end and moving to the center of the box, in order to avoid segregation of aggregates. A small plastic box with rectangular edges was used to sample from 25 to 30 g of air-dry aggregates in all extension of previous right-end-left disposal. At the same time, 10 to 15 g were sampled to determine gravimetric water content.

For size distribution determination, a nest of sieves with opening of 4.00, 2.00, 1.00, 0.50, and 0.25 mm was used. At the bottom, aggregates which pass through a sieve with 0.25 mm open were collected. The aggregate sample was spread on the upper sieve and the set was submitted to 12 gentle right-and-left movements, turned 90º and submitted again to 12 gentle right-and-left movements, to allow that only aggregates with diameter greater than the respective open mesh of each sieve could kept on it, without applying excessive disruption energy. Mass of aggregates retained on each sieve was used for calculation of mean weigh diameter (MWD_{AD}) and geometric mean diameter (GMD_{AD}) using, respectively, the following equations:

$$MWD_{AD} = \sum_{1=1}^{6}(ri.di), \qquad (2.1)$$

and

$$GMD_{AD} = EXP\left[\sum_{i=1}^{6}(ri.\ln di)\right] \qquad (2.2)$$

where i denotes the aggregate classes (8.00-4.00; 4.00-2.00; 2.00-1.00; 1.00-0.50; 0.50-0.25; and < 0.25 mm), r_i the ratio of aggregate mass from i class related to total, and d_i the mean diameter for class i.

2.4.4 Wet-aggregate size distribution and stability index

The aggregates from all sieves of previous determination were placed together to perform wet-aggregate stability determination. For this determination, a methodology similar to modified Kemper & Chepil method (Kemper & Chepil, 1965) was used. Nests of sieves with openings of 4.00, 2.00, 1.00, and 0.50 mm were placed inside individual tubes. The water level in each tube was enough to touch the bottom of the top sieve on the upstroke of the apparatus. Aggregate sample was spread on the top sieve and allowed to saturate by capillarity during approximately 1 minute and then the water level was rise until the sample in top sieve was just covered. Samples remained in this condition for 10 minutes since initial wetting, when after the apparatus was turned on during 10 minutes, applying raise-and-lower of approximately 40 mm through the water in 42 times per minute. The nests of sieves were removed and the aggregates remained on each sieve were passed to individual can, oven-dried and weighed, to determine aggregate mass of each class. Aggregates with diameter les than 0.50 mm were sieved on a 0.25 mm opening sieve and washed with fresh water, in order to separate them in two classes: 0.50-0.25 and < 0.25 mm diameter. The aggregates from 0.50-0.25 mm diameter class were transferred to an individual can, oven-dried and weighed. The mass of aggregates less then 0.25 mm diameter was determined as the difference of the total mass of aggregates (oven-dry mass) and the sum of oven-dry mass of aggregate classes greater then 0.25 mm diameter. Because the low sand content (< 3%) in surface horizons, it was not removed to determine aggregate stability.

The mean weight diameter (MWD_{WS}) and geometric mean diameter (GMD_{WS}) of water stable aggregates were determined using the same equations as described for size distribution of air-dry aggregates. Additionally, aggregate stability index (SI) was determined throughout the relation between water stable and air-dry mean diameter for both weigh/arithmetic (SI_{MWD}) and geometric (SI_{GMD}) calculation:

$$\mathbf{SI_{MWD} = MWD_{WS}/MWD_{AD}} \quad (2.3)$$

$$\mathbf{SI_{GMD} = GMD_{WS}/GMD_{AD}} \quad (2.4)$$

2.4.5 Chemical analysis

Chemical analysis was performed in disturbed samples collected at the same time as soil core sample, at 0-5, 5-10, 10-20 and 20-40 cm layers. Soil for chemical analysis was sampled at four positions in each plot, mixed, oven-dried at 60º C during 48 hours, ground with an electronic device and stored in paper boxes. The chemical analysis was performed at Laboratory for Soil Analysis of the Research Centre for Familiar Agriculture (Chapecó, SC), using methodology described in Tedesco et al. (1985).

2.4.6 Statistical analysis

Statistical analysis was performed using the Statistical Analysis System software (SAS, 1989). ANOVA test was run for quantifying variances among soil tillage, nutrient source, depths and sampling time. Means differences were compared using the Tukey test ($P< 0.05$). Because of covariance between gravimetric water content and aggregate stability, general linear models procedure was performed to determine means differences among tillage systems within each depth, among depths within each tillage system, and among tillage systems across sampling time. Pearson correlation was established among aggregate stability indexes and soil properties.

2.5 Results and discussion

Soil tillage showed differences for mean diameter of water stable aggregates and stability index, both for arithmetic and geometric calculation (Table 2.2). Dry and wet-aggregate size distribution and stability indexes showed differences among soil tillage, sampling depths and interaction between these two sources of variation at the end of the ninth year of applying the treatments. Nutrient sources treatments showed smaller differences among them and no interaction with soil tillage and depth. Aggregates from soil cores sampled at five times during the tenth year showed statistical differences among soil tillage for geometric mean diameter of water stable aggregates and stability indexes among sampling times, depths (except MWD_{WS}), and interactions between sampling times and depths or soil tillage systems for some parameters (Table 2.3). In both studies, the coefficient of variation was high, especially for mean diameter of water stable aggregates and stability indexes, which can be explained partially by the variation in gravimetric water content of aggregates at time of aggregate stability determination.

Table 2.2 - Analysis of variance (ANOVA) for size distribution and aggregate stability indexes determined at four depths after nine years of applying five soil tillage systems and five nutrient sources.

Sources of variation		Size distribution and aggregate stability indexes					
	U	MWD_{AD}	GMD_{AD}	MWD_{WS}	GMD_{WS}	SI_{MWD}	SI_{GMD}
Soil tillage (ST)	**	***	***	***	***	***	***
Nutrient source (NS)	ns	*	*	**	**	*	*
ST x NS	ns	ns	ns	ns	ns	ns	ns
Depth	***	***	***	***	***	***	***
Depth x ST	***	***	***	***	***	***	***
Depth x NS	ns	ns	ns	ns	ns	ns	ns
CV%	21.0	8.7	12.3	22.2	25.5	20.0	22.2

U = gravimetric water content; MWD_{AD} = mean weigh diameter of air-dry aggregates; GMD_{AD} = geometric mean diameter of air-dry aggregates; MWD_{WS} = mean weigh diameter of water stable aggregates; GMD_{WS} = geometric mean diameter of water stable aggregates; SI_{MWD} = stability index of aggregates considering mean weigh diameter; and SI_{GMD} = stability index of aggregates considering geometric mean diameter.
***, **, * , and ns = respectively statistical significance at 0.1, 1 and 5% level and no significance.

Gravimetric water content showed the best correlation with aggregate stability in water, both for mean diameter of water stable aggregates and stability indexes in soil sampled after nine years of applying treatments (Table 2.4). When dry aggregates are allowed to saturate in contact with water at atmospheric pressure, air bubbles are entrapped inside the aggregate and are compressed by water pulled into it by capillarity until the air bubble bursts out of the partially wetted aggregate, resulting in its partial disintegration (Kemper & Koch, 1966). The wetter the aggregate, the smaller the effect of air bubbles entrapment, which reflected in high positive correlation between gravimetric water content and aggregate stability (Table 2.4 and Figure 2.1).

Table 2.3 - Analysis of variance (ANOVA) for size distribution and aggregate stability indexes determined at two depths in five sampling times during the tenth year of applying five soil tillage systems and mineral nutrient source.

Sources of variation	Size distribution and aggregate stability indexes						
	U	MWD_{AD}	GMD_{AD}	MWD_{WS}	GMD_{WS}	SI_{MWD}	SI_{GMD}
Soil tillage (ST)	ns	ns	ns	***	***	***	***
Sampling time	***	***	***	***	***	***	***
ST x Sampling time	ns	ns	**	ns	**	ns	ns
Depth	ns	***	***	ns	**	***	***
Depth x ST	ns	ns	ns	ns	ns	**	ns
Depth x Sampling time	ns	***	***	ns	**	ns	ns
CV%	36.1	13.6	18.1	23.2	24.3	16.0	17.0

U = gravimetric water content; MWD_{AD} = mean weigh diameter of air-dry aggregates; GMD_{AD} = geometric mean diameter of air-dry aggregates; MWD_{WS} = mean weigh diameter of water stable aggregates; GMD_{WS} = geometric mean diameter of water stable aggregates; SI_{MWD} = stability index of aggregates considering mean weigh diameter; and SI_{MGD} = stability index of aggregates considering geometric mean diameter.
***, **, * , and ns = respectively statistical significance at 0.1, 1 and 5% level and not significant.

Table 2.4 - Pearson correlation coefficients between size distribution and aggregate stability indexes with physical and chemical attributes determined at four depths after nine years of applying five soil tillage systems and five nutrient sources.

Attributes	Size distribution and aggregate stability indexes					
	MWD_{AD}	GMD_{AD}	MWD_{WS}	GMD_{WS}	SI_{MWD}	SI_{GMD}
U	0.28***	0.31***	0.73***	0.65***	0.68***	0.59***
Bulk density	0.71***	0.71***	0.46***	0.44***	0.15**	0.04^{ns}
pH	0.03^{ns}	0.05^{ns}	0.32***	0.25***	0.34***	0.27***
H + Al	0.00^{ns}	0.00^{ns}	-0.21***	-0.18**	-0.24***	-0.22***
Organic matter	-0.15*	-0.12*	0.34***	0.18**	0.43***	0.29***
Available phosphorus	-0.34***	-0.31***	0.21***	0.11*	0.40***	0.36***
Exchangeable K	-0.38***	-0.36***	0.26***	0.09^{ns}	0.46***	0.35***
Exchangeable Ca	0.00^{ns}	0.03^{ns}	0.45***	0.36***	0.50***	0.43***
Exchangeable Mg	0.04^{ns}	0.06^{ns}	0.36***	0.29***	0.37***	0.32***

MWD_{AD} = mean weigh diameter of air-dry aggregates; GMD_{AD} = geometric mean diameter of air-dry aggregates; MWD_{WS} = mean weigh diameter of water stable aggregates; GMD_{WS} = geometric mean diameter of water stable aggregates; SI_{MWD} = stability index of aggregates considering mean weigh diameter; and SI_{GMD} = stability index of aggregates considering geometric mean diameter; U = gravimetric water content.
***, **, * , and ns = respectively statistical significance at 0.1, 1 and 5% level and no significance.

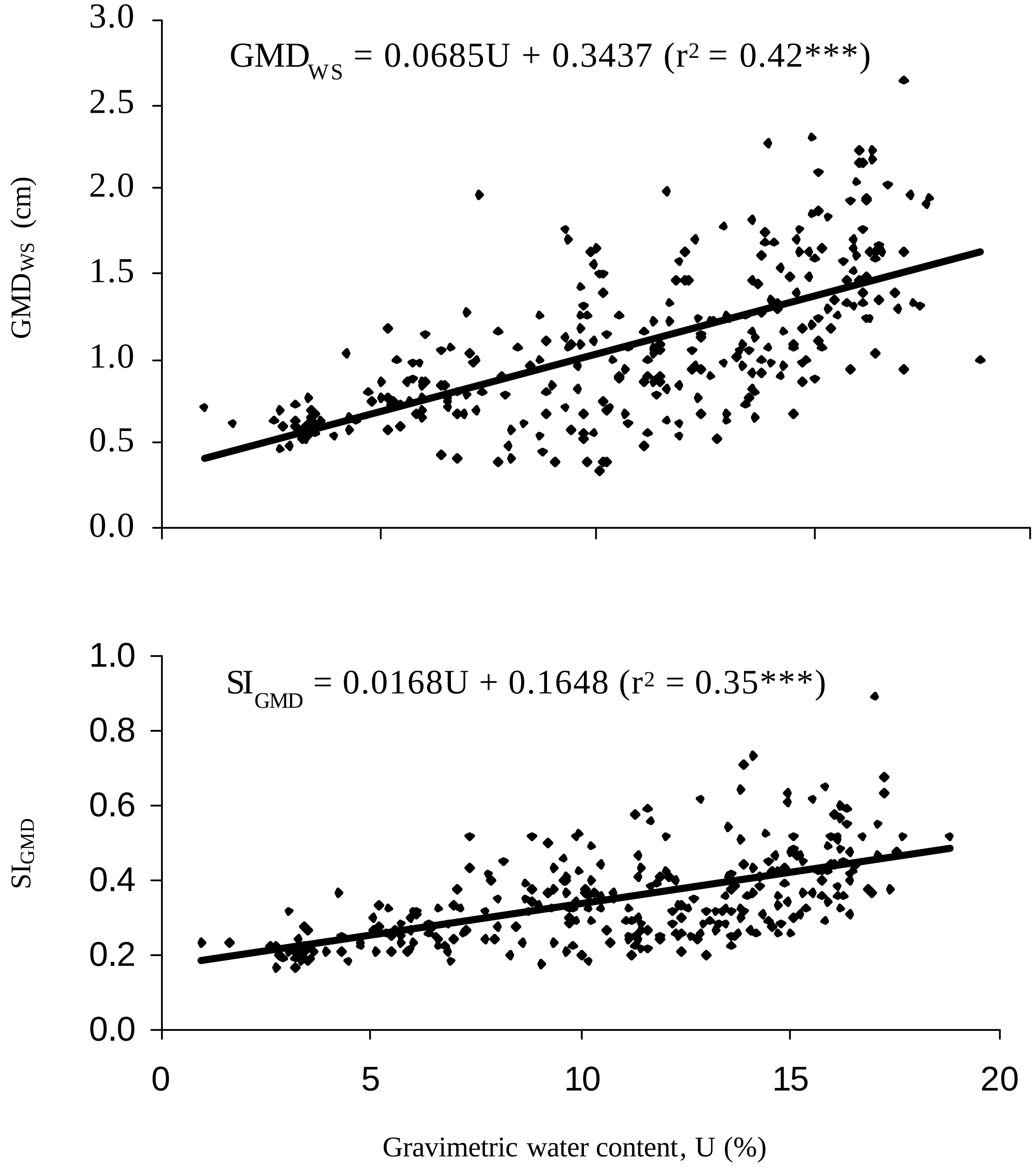

Figure 2.1 - Correlation between gravimetric water content (U) at time of aggregate stability test and geometric mean diameter of water stable aggregates (GMD_{WS}) and aggregate stability index for geometric mean diameter (SI_{GMD}) for cores sampled at four depths after nine years of applying five soil tillage systems and nutrient sources.

Size distribution of air-dry aggregates, on the other hand, was strongly affected by the bulk density, determined at the same core as used to sample aggregates (Table 2.4 and Figure

2.2). Since almost the whole volume of the soil core sampled was used in this determination, the greater the bulk density, the greater the mean diameter of aggregates obtained by the disruption of soil core. This correlation can explain part of differences found in size distribution values showed in Table 2.5. It means that there is a good correlation between soil compaction and size distribution of air-dry aggregates, and greater values of mean diameter found in some soil tillage treatments or depths might be due partially to greater compaction degree. Greater mean diameter of air-dry aggregates can be due to physical approximation of soil particles caused by external stress without subsequent stabilization, since the effect of bulk density on water stability was lower (correlation coeficient of 0.71, 0.44, and 0.04 between bulk density and, respectively, GMD_{AD}, GMD_{WS}, and SI_{GMD}) as observed also by Silva & Mielniczuk (1997). Carpenedo & Mielniczuk (1990) pointed out that the greater aggregate stability found in NT compared to CT was not reflected in better quality of soil aggregates, because in both tillage systems the aggregates were compacted, with predominance of micropores, while aggregates from perennial cultivated grass, savanna or forest showed higher macroporosity and total porosity. Bulk density was also highly but positively correlated with mean diameter of water stable aggregates (Figure 2.2), but not with stability indexes, supporting what was stated above.

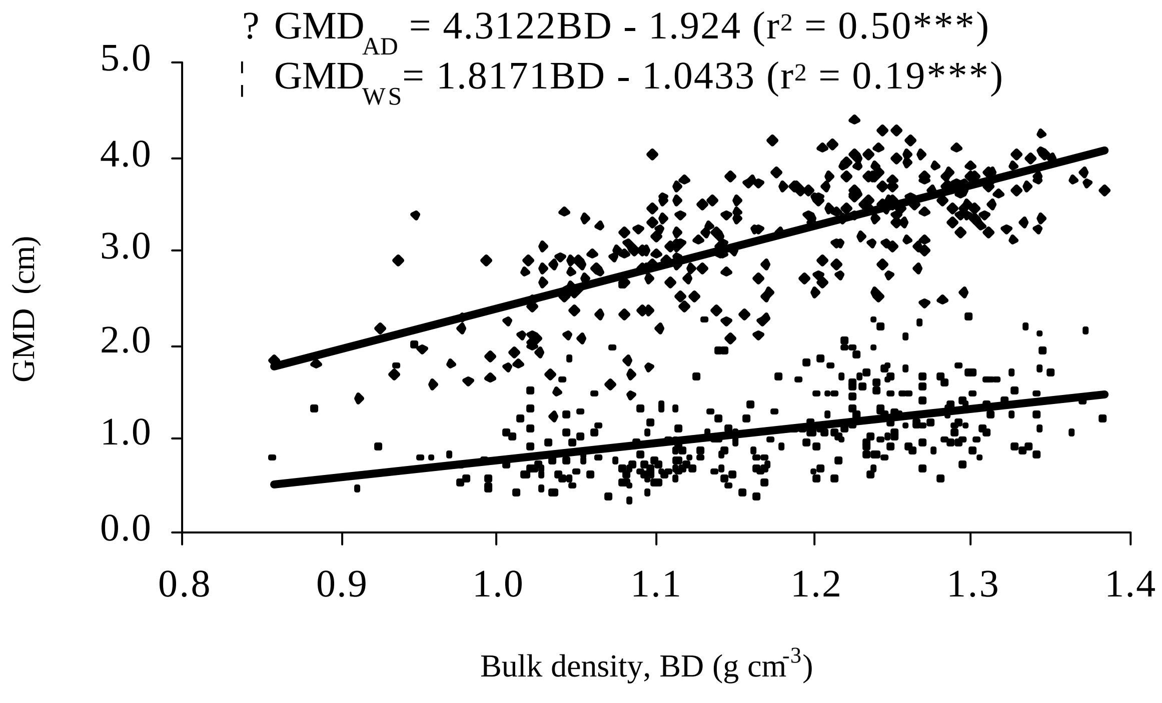

Figure 2.2 - Correlation between bulk density (BD) and geometric mean diameter of air-dry (GMD_{AD}) and water stable (GMD_{WS}) aggregates for cores sampled at four depths after nine years of applying five soil tillage systems and nutrient sources.

Table 2.5 - Size distribution and aggregate stability indexes at four depths after nine years of applying five soil tillage systems (averaged across nutrient sources).

Depth (cm)	Soil tillage system				
	NT	CP	CT	CTb	CTr
	Geometric mean diameter of air-dry aggregates - GMD_{AD} (mm)				
0 – 5	2.95 a C	2.47 b C	2.12 bc C	1.94 c C	2.12 bc C
5 – 10	3.42 a AB	3.53 a A	3.63 a A	3.47 a AB	3.27 a AB
12 – 17	3.56 ab A	3.80 a A	3.74 ab A	3.71 ab A	3.46 b A
27 – 32	3.14 a BC	3.07 a B	2.89 a B	3.11 a B	3.04 a B
	Geometric mean diameter of water stable aggregates – GMD_{WS} (mm)				
0 – 5	1.76 a A	1.12 b BC	0.94 b B	0.57 c B	0.58 c C
5 – 10	1.17 bc B	1.38 b AB	1.68 a A	1.13 bc A	0.95 c B
12 – 17	1.42 ab B	1.41 ab A	1.51 a A	1.16 b A	1.13 b A
27 – 32	0.78 ab C	0.86 a C	0.71 b B	0.70 b B	0.70 b C
	GMD_{WS} corrected to antecedent water content within soil depth (mm)				
0 – 5	1.62 a	1.14 b	0.90 c	0.66 d	0.66 d
5 – 10	1.19 c	1.39 b	1.66 a	1.11 cd	0.96 d
12 – 17	1.32 ab	1.47 a	1.51 a	1.22 bc	1.11 c
27 – 32	0.76 ab	0.82 a	0.76 ab	0.70 b	0.70 b
	GMD_{WS} corrected to antecedent water content within soil tillage (mm)				
0 – 5	1.59 A	1.09 B	0.87 C	0.65 B	0.60 B
5 – 10	1.15 B	1.29 A	1.55 A	0.87 AB	0.88 A
12 – 17	1.22 B	1.22 AB	1.33 AB	0.87 AB	0.97 A
27 – 32	1.17 B	1.17 AB	1.09 BC	1.17 A	0.91 A
	Aggregate stability index for geometric mean diameter – SI_{GMD}				
0 – 5	0.59 a A	0.45 b A	0.45 b A	0.29 c A	0.28 c AB
5 – 10	0.34 bc B	0.40 b B	0.46 a A	0.32 c A	0.29 c A
12 – 17	0.40 ab B	0.37 abc B	0.40 a A	0.31 c A	0.33 bc A
27 – 32	0.25 ab C	0.28 a C	0.24 ab B	0.22 b B	0.23 b B
	SI_{GMD} corrected to antecedent water content within soil depth				
0 – 5	0.54 a	0.46 b	0.43 b	0.32 c	0.31 c
5 – 10	0.35 bc	0.39 b	0.46 a	0.32 cd	0.29 d
12 – 17	0.37 a	0.39 a	0.40 a	0.33 b	0.32 b
27 – 32	0.24 bc	0.27 a	0.26 ab	0.22 c	0.23 bc
	SI_{GMD} corrected to antecedent water content within soil tillage				
0 – 5	0.55 A	0.45 A	0.42 A	0.31 A	0.29 A
5 – 10	0.34 B	0.38 B	0.41 A	0.26 A	0.27 A
12 – 17	0.35 B	0.34 B	0.34 B	0.25 A	0.29 A
27 – 32	0.34 B	0.32 B	0.39 AB	0.32 A	0.28 A

NT = no-till; CP = chisel plow; CT = conventional tillage; CTb = CT with crop residues burned; and CTr = CT with crop residues removed.

Means followed by the same small letters at a given row and capital letter at a given column are not statistically different (Tukey, $P < 0.05$).

All chemical parameters had highly significant and positive correlation with stability indexes (SI) of aggregates, and only potential acidity (H + Al) showed negative correlation (Table 2.4), which could be related to the fact that the higher H + Al values, the lower the exchangeable cation values. Exchangeable cations act as bridges between organic colloids and clay, and multivalent cations are more efficient in promoting stabilization than monovalent ones (Oades, 1984).

Organic matter effect on aggregate stability has been confirmed in several studies (Campos et al., 1995; Silva & Mielniczuk, 1998; D'Andréa et al., 2002; Castro Filho et al., 1998; Kemper & Koch, 1966) and the organic binding agents can have a transient, temporary or persistent effect, depending on which binding agent is involved in stabilization (Tisdall & Oades, 1982). The correlation between pH, H + Al and available phosphorus and aggregate stability probably is due to association of these parameters with others involved in aggregate formation and stabilization.

Because of similar behavior between mean weight diameter and geometric mean diameter, only results of the second one were showed and discussed. Geometric mean diameter of air-dry aggregates was greater at intermediate layers and lower at surface layer (Table 2.5). At those layers, the bulk density was greater (Chapter 1), showing close association between both parameters (Table 2.4 and Figure 2.2). Differences among soil tillage systems were found at 0-5 and 12-17 cm layers. After nine years of applying soil tillage systems NT e CP showed higher GMD_{AD} at 0-5 cm layer, but no differences were found at the upper layer (2.5-7.5 cm layer) when considering all five sampling times performed during the tenth year (Table 2.6). The greater values at upper layer of NT and CP can be explained by the higher organic matter content but also because the lower soil mobilization by soil tillage compared to conventional systems (CT, CTb and CTr). This statement can be confirmed by the increase in GMD_{AD} at 240 and 360 days after seeding (Table 2.7), when natural soil consolidation took place, resulting in increasing aggregation as evaluated in soil sampled in cores, when the whole soil mass was analyzed.

There were differences in geometric mean diameter of water stable aggregates among soil tillage systems and soil depths (Table 2.5). Since this determination was highly correlated with aggregate water content at time of aggregate stability analysis (Table 2.4 and Figure 2.1), differences among means were also compared through least square means, using general linear models procedure (SAS, 1989), both for soil tillage within each depth and for soil depth within each soil tillage. This procedure improved means differentiation among soil tillage in each depth (despite low variability in aggregate water content within each depth), and corrected values of means among soil depths, which had greater variation in aggregate water content due to variation in storage time among them (data not shown).

Table 2.6 - Bulk density, gravimetric water content at time of water aggregate stability test, size distribution and aggregate stability indexes at two depths and in five tillage systems (averaged across sampling times performed during the tenth year).

Parameters	Soil tillage system				
	NT	CP	CT	CTb	CTr
			2.5 – 7.5 cm		
BD	1.17 a	1.08 b	1.09 ab	1.06 b	1.10 ab
U	8.1 a	6 .9 a	8.0 a	6.6 a	6.8 a
GMD_{AD}	2.21 a	2.16 a	2.12 a	1.93 a	1.91 a
GMD_{WS}	1.11 a	0.95 a	0.91 a	0.67 b	0.60 b
GMD_{WSC}	1.10 a	0.96 ab	0.90 b	0.68 c	0.61 c
SI_{GMD}	0.52 a	0.46 ab	0.44 b	0.35 c	0.32 c
SI_{GMDC}	0.51 a	0.46 ab	0.43 b	0.36 c	0.33 c
			12.5 – 17.5 cm		
BD	1.25 a	1.22 a	1.23 a	1.21 a	1.23 a
U	8.3 a	7.3 a	8.1 a	7.7 a	7.9 a
GMD_{AD}	2.49 a	2.72 a	2.58 a	2.54 a	2.35 a
GMD_{WS}	1.04 ab	1.05 a	1.03 ab	0.80 bc	0.75 c
GMD_{WSC}	1.03 a	1.06 a	1.03 a	0.80 b	0.75 b
SI_{GMD}	0.42 a	0.39 a	0.39 a	0.32 b	0.32 b
SI_{GMDC}	0.42 a	0.40 a	0.39 a	0.32 b	0.32 b

GMD_{AD} = geometric mean diameter of air-dry aggregates; GMD_{WS} = geometric mean diameter of water stable aggregates; GMD_{WSC} = geometric mean diameter of water stable aggregates corrected to aggregate water content; SI_{GMD} = stability index of aggregates considering geometric mean diameter; SI_{GMDC} = stability index of aggregates considering geometric mean diameter corrected to aggregate water content; U = gravimetric water content; and BD = bulk density.
Means followed by the same small letters at a given row are not statistically different (Tukey, $P< 0.05$).

Greater differentiation in GMD_{WS} among tillage systems were found at upper layers (Table 2.5). NT system showed greater GMD_{WS} at 0-5 cm layer, CT at 5-10 and 12-17 cm layer, and CP intermediate values in between NT and CT. Similar trend as 0-5 cm was observed at 2.5-7.5 cm layer when soil cores were sampled at five times during the tenth year of applying treatments (Table 2.6). These results can be explained by the differences among soil tillage systems concerning to crop residues disposition after tillage (on the surface in NT, partly incorporated in CP and incorporated at plow layer in CT) and consequently the aggregate stability promoted by transient and temporary organic binding agents resulting from the crop residue decomposition (Tisdall & Oades, 1982). This statement is confirmed by the much lower values of GMD_{WS} found at three upper layers in tillage treatments where crop residues were burned (CTb) or removed from the field (CTr). Similar trend among tillage systems was observed in stability index (SI_{GMD}).

Table 2.7 - Bulk density, gravimetric water content at time of water aggregate stability test, size distribution and aggregate stability indexes at two depths and in five sampling times performed during the tenth year (averaged across tillage systems).

Parameters	Sampling times (days after seeding)				
	1	60	120	240	360
			2.5 – 7.5 cm		
BD	1.05 b	1.08 b	1.10 b	1.09 b	1.18 a
U	4.7 b	10.3 a	4.8 b	12.0 a	4.5 b
GMD_{AD}	1.87 b	1.97 b	1.80 b	2.23 ab	2.46 a
GMD_{WS}	0.81 a	0.86 a	0.82 a	0.88 a	0.87 a
GMD_{WSC}	0.87 a	0.79 a	0.88 a	0.77 a	0.94 a
SI_{GMD}	0.45 ab	0.45 ab	0.46 a	0.38 bc	0.35 c
SI_{GMDC}	0.48 a	0.41 b	0.49 a	0.32 c	0.38 bc
			12.5 – 17.5 cm		
BD	1.21 b	1.21 b	1.22 b	1.20 b	1.30 a
U	4.7 c	10.1 b	5.3 c	14.0 a	5.1 c
GMD_{AD}	2.31 bc	2.06 c	2.10 c	3.55 a	2.66 b
GMD_{WE}	0.87 b	0.83 b	0.83 b	1.24 a	0.88 b
GMD_{WEC}	0.94 ab	0.78 b	0.89 ab	1.10 a	0.95 ab
SI_{GMD}	0.38 a	0.41 a	0.39 a	0.35 ab	0.32 b
SI_{GMDC}	0.40 a	0.39 ab	0.41 a	0.30 b	0.34 b

GMD_{AD} = geometric mean diameter of air-dry aggregates; GMD_{WS} = geometric mean diameter of water stable aggregates; GMD_{WSC} = geometric mean diameter of water stable aggregates corrected to aggregate water content; SI_{GMD} = stability index of aggregates considering geometric mean diameter; SI_{GMDC} = stability index of aggregates considering geometric mean diameter corrected to aggregate water content; U = gravimetric water content; and BD = bulk density
Means followed by the same small letters at a given row are not statistically different (Tukey, $P < 0.05$).

Only NT system showed greater GMD_{WS} at surface layer. The others management systems showed higher GMD_{WS} at intermediate or lower sampling depths. Regarding to SI_{GMD}, greater values were found at surface layer (0-5 cm) in management systems with crop residues kept in the field and there were no differences among depths when crop residues were burned (CTb) or removed (CTr).

Nutrient sources showed little effect on size distribution of air-dry and water stable aggregate and no effect on stability index by Tukey test (Table 2.8). Among nutrient sources, poultry litter and cattle manure showed greater mean diameter than others, probably because in both manure there is greater amount of organic material with high C:N ratio, from which persistent binding agents are derived, as well as greater fungi development during decomposition (Tisdall & Oades, 1982). The low effect of nutrient sources on size distribution and aggregate stability can be associated to high soil clay content (> 70% in upper layers), since the effect of organic matter is more pronounced in soils containing smaller amounts of clay (Baver et al., 1972) or with high amount of organic material application (Weil & Kroontje, 1979).

Table 2.8 - Size distribution and aggregate stability indexes after nine years of applying five nutrient sources (averaged across soil tillage systems and four depths).

Nutrient source	Size distribution and aggregate stability indexes					
	MWD_{AD}	GMD_{AD}	MWD_{WS}	GMD_{WS}	SI_{MWD}	SI_{GMD}
	---------------------------------- mm --					
Control	3.99 A	3.08 AB	1.66 A	1.03 BC	0.41 A	0.33 A
Mineral fertilizers	3.94 A	3.03 B	1.68 AB	1.01 C	0.43 A	0.33 A
Poultry litter	4.09 A	3.22 A	1.86 A	1.18 A	0.46 A	0.36 A
Cattle manure	4.09 A	3.21 AB	1.84 AB	1.16 AB	0.45 A	0.36 A
Pig manure	3.96 A	3.08 AB	1.65 A	1.03 BC	0.42 A	0.34 A

MWD_{AD} = mean weigh diameter of air-dry aggregates; GMD_{AD} = geometric mean diameter of air-dry aggregates; MWD_{WS} = mean weigh diameter of water stable aggregates; GMD_{WS} = geometric mean diameter of water stable aggregates; SI_{MWD} = stability index of aggregates considering mean weigh diameter; and SI_{GMD} = stability index of aggregates considering geometric mean diameter.
Means followed by the same letter at a given column are not statistically different (Tukey, $P < 0.05$).

2.6 Conclusions

Dry-aggregate size distribution was strongly affected by the bulk density and greater values of geometric mean diameter of the air-dry aggregates were found in soil tillage with lesser soil mobilization (NT and CP), or in compacted layer in conventional tillage treatments (CT, CTb, and CTr).

Wet-aggregate stability measured by geometric mean diameter of water stable aggregates (GMD_{WS}) and stability index (SI_{GMD}) showed high correlation with previous gravimetric water content of aggregates.

Greater differentiation among tillage systems were found in GMD_{WS} at superficial layer, where NT showed greater values. Conventional tillage showed greater values at 5-10 and 12-17 cm layer and CP intermediate values in between NT and CT.

Nutrient sources had lesser effect on aggregate stability than tillage systems after nine years of annually applications.

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CAPÍTULO 3. COMPRESSIBILIDADE E RESISTÊNCIA À PENETRAÇÃO DE UM NITOSSOLO VERMELHO SUBMETIDO A DIFERENTES SISTEMAS DE PREPARO.

3.1 Resumo

A tensão de precompressão define a transição entre a curva de recompressão e a reta virgem na curva de tensão-deformação do solo, constituindo-se em uma estimativa da maior pressão suportada previamente por este. Em solos com horizontes ou camadas marcadamente diferenciados, cada camada apresente uma resistência mecânica bem definida, a qual pode ser quantificada pela sua tensão de precompressão. Determinações de resistência à penetração, por outro lado, podem ser utilizadas para estudar o perfil de resistência do solo no campo. O efeito de longo prazo de sistemas de preparo do solo sobre propriedades físicas e mecânicas foi determinado em amostras com estrutura preservada e alterada, coletadas no décimo ano de experimentação a 5 e 15 cm de profundidades (respectivamente 3.5-6.5 e 13.5-16.5 cm), seis meses após a aplicação dos tratamentos de preparo (PD = plantio direto; PE = escarificação + gradagem e; PC = aração + 2 gradagens), com a aplicação de adubação mineral e cama de aviário (5 Mg ha^{-1} a^{-1}, base úmida). O teste de compressibilidade foi efetuado em condições confinadas, com tensões normais variando de 10 a 400 kPa, com registro automático das mudanças de altura e de pressão de água nos poros, o que permitiu o cálculo da tensão de precompressão considerando a tensão efetiva. A resistência à penetração foi determinada no campo após a semeadura da cultura do milho na safra 2003/2004, em três posições: linha de semeadura (LS), entrelinha sem tráfego (EST) e entrelinha com tráfego recente (ECT). O PD apresentou maior resistência do solo à deformação, como indicado pelos maiores valores de tensão de precompressão e menores do coeficiente de compressibilidade comparativamente aos tratamentos com preparo do solo. Quando a estrutura natural do solo foi eliminada (amostras com estrutura alterada), menores diferenças foram encontradas. A tensão de precompressão, o coeficiente de compressibilidade e a resistência à penetração foram relacionados com a densidade do solo. A adição de matéria orgânica extra através de cama de aviário resultou em redução da tensão de precompressão em amostras com estrutura preservada. Os perfis de resistência à penetração mostraram diferenças significativas entre sistemas de preparo na camada superficial da entrelinha sem tráfego recente, onde o PD apresentou os maiores valores. Pequenas diferenças foram encontradas na linha de semeadura (com valores menores) e nas entrelinhas com tráfego recente (com valores maiores), mostrando que mesmo o tráfego de um trator leve após as operações de preparo pode reduzir drasticamente o efeito do preparo na redução da resistência do solo. Por outro lado, a existência de um equipamento apropriado para cortar e revolver o solo na linha de semeadura pode ser suficiente para remover o efeito da compactação superficial e favorecer o crescimento radicular das culturas.

Palavras-chaves: preparo do solo, tensão de precompressão, resistência à penetração.

SOIL COMPRESSIBILITY AND PENETRABILITY OF A HAPLORTHOX IN SOUTHERN BRAZIL AS AFFECTED BY A LONG-TERM TILLAGE SYSTEMS

3.2 Abstract

The precompression stress value defines the transition from the reloading curve to the virgin compression line in stress-strain curve, being an estimative of the highest load previously supported by the soil. In soils with markedly differentiated soils horizons or layers, each layer has a well defined mechanical strength which can be quantified by its precompression stress. Penetration resistance measurements, on the other hand, can be used to determine soil strength profiles in the field. The effect of long-term tillage systems on physical and mechanical properties was determined in undisturbed and remolded samples collected at 5 and 15 cm depth six months after applying no-till (NT), chisel plow (CP) and conventional tillage (CT) treatments, with the application of mineral fertilizers and poultry litter. The compressibility test was performed under confined conditions with normal loads varying from 10 to 400 kPa, with automatic recorder of the height changes and changes in pore water pressure, which allow calculating the precompression stress values considering effective stress. Penetration resistance was determined in the field after seeding, in three positions: seeding row (SR), untrafficked interrow (UI), and recently trafficked interrow (TI). No-till system showed greater soil resistance to deformation, as determined by the higher precompression stress, and lower coefficient of compressibility than tilled treatments. When original soil structure was destroyed (remolded samples), less differences were found. The precompression stress, compressibility coefficient and penetration resistance were related to bulk density, and the addition of extra organic matter (poultry litter) resulted in reduction of precompression stress in undisturbed samples. Penetration resistance profiles showed greater differences among tillage treatments in the upper layer of the untrafficked interrow, where NT system showed the higher values. Small differences were found at seeding row (with lower values) and in recently trafficked interrow (with higher values), showing that even traffic with a light tractor after soil tillage reduced drastically the effect of previous tillage in loosening up the soil. On the other hand, an appropriate apparatus to cut the soil and open the furrow for seeding in direct seeding machine was enough to realleviate surface soil compaction to allow root growth.

Keywords: soil tillage, precompression stress, penetration resistance, Oxisol.

3.3 Introduction

The mass of various machines used in agricultural operations has increased by a factor of 3 to 4 during the last three decades, while the number of field operations can be greater then 10 per year (Horn, 1995). As a consequence, increasing interest in surface and subsoil compaction has been focused in order to protect the soil against detrimental effects on physical, chemical, and biological soil properties and processes in deeper layers, which cannot be easily realleviated by tillage implements or inexpensive practices (Håkansson and Reeder, 1994). Additional interest might be focussed on soil compaction caused by animal trampling in fields used seasonally for grazing, since the hoof pressure can result in a compaction degree even greater than that one caused by tires, especially when animals are walking (Willat & Pullar, 1983).

From basic soil mechanics, the normal stress on any plane is in general the sum of the stresses transmitted by solids particles (effective) and the pressure of the fluid in the void space (neutral). The effective stress (s') for saturated soils is given by the expression proposed by Terzaghi:

$$\mathbf{s' = s - \mathit{u}} \qquad (3.1)$$

where **s** denotes total normal stress and ***u*** denotes fluid pressure in the pore space.

In unsaturated soils, air and water in the pore space also affects the stress transmission (Bishop, 1961). Thus, the corresponding expression for the effective stress in all situations is defined as:

$$\mathbf{s' = s - \mathit{u}_a + ?\ (\mathit{u}_a - \mathit{u}_w)} \qquad (3.2)$$

where $\boldsymbol{u_a}$ denotes pressure in the gas and vapor phase and $\boldsymbol{u_w}$ denotes pressure in the pore water. The values of the **?** parameter are unity for saturated soils (when the equation is reduced to a two-phase system as proposed by Terzaghi), and zero for dry soils (pF 7). The intermediate values will depend primarily on the saturation degree (Bishop, 1961). Another special case arises when $\boldsymbol{u_a}$ is equal to atmospheric pressure, which reduces the effective stress equation to $\mathbf{s' = s - ?\ \mathit{u}_w}$ (3.3) (Skempton, 1961). Especially for long-term loading, this equilibration will occur between internal and external pore air pressure in uniaxial confined test. Although this type of equation is well-known since many decades, the calculation of the effective stress is mostly not considered in the calculation of the precompression stress because neither the determination of pore water pressure nor information about the ? factor were available. Depending on soil type and processing conditions, saturation degree and ? factor present different behavior, but in overall terms the relation can be considered as being 1:1 in higher saturation degree (Horn & Baumgartl, 1999).

The simultaneous registration of soil settlement and pore water pressure during stress strain tests under confined conditions allow studying the relationship between soil deformation and water suction during multi-step soil compressibility determination. Fazekas & Horn (2004) found that increasing time between applied loads increased soil settlement and reduced pore water pressure and precompression stress values. Greater time intervals allow water to redistribute in the whole soil sample and result in an equilibration in the pore water pressure (since part of water can be lost during the test) in the remaining pore volume and pore size distribution. The more negative the pore water pressure remains, the higher is the effective stress which in itself shows a clear dependency to the loading time and the corresponding stresses applied.

In soils with markedly differentiated soil horizons or layers, each layer has a well defined mechanical strength value which can be quantified by its precompression stress and if the applied stress does not exceed this value, the soil horizon reacts elastically, while exceeding it results in further plastic deformation (Horn et al., 1995). Furthermore, deeper soil horizons will be also subjected to an additional soil compaction as long as their internal strength is smaller than the remaining stress applied. Soil tillage systems affect mechanical behaviour of soil layers. Horn (1986, 2004) determined that soils under a long-term conservation tillage induced changes in physical properties compared with conventionally-tilled soils, being more resistant and thus less susceptible to deformation. Differences in precompression stress, shear strength and hydraulic conductivity were found at 10-15 cm after approximately 3 years, at 30-35cm after 5 to 6 years, and at 55-60 cm the same trend started after around 7 years (Horn, 2004). He also concluded that, under climatic conditions prevailing in northern Germany, better functioning pore systems can be obtained under a continuously applied system of conservation tillage, but these findings could only be maintained if during all tillage operations the internal soil strength is never exceeded by the applied mechanical stress.

Penetration resistance measurements can be used to determine soil strength profiles in the field, being suitable in detecting strength and structural discontinuities associated with wheel tracks and size of structural units (Lowery & Morrison, 2002). Since this determination is highly influenced by soil water content, measurements in the field must be done when soil water content is uniform in all profile, i.e. when they are nearly at field capacity, which is obtained 3-5 days after a rainfall with high precipitation. Shafiq et al. (1994) determined that penetration resistance increased with the increase in degree of compaction and this increase was more pronounced when compaction was induced at higher antecedent soil water contents. Greater penetration resistance is found in upper layers in no-till compared with conventional tillage systems (Francis et al., 1987; Burch et al., 1986) and chisel plow (Stewart & Vyn, 1994). When additional load (12 t axle load) was applied before tillage, significant differences in penetrometer resistance were restricted to depths of less than 35 cm in any of the tillage system (Stewart & Vyn, 1994). Genro Junior et al. (2004) found higher penetration resistance at about 10 cm depth in no-till and reduced values up and down to. This determination highly depended on soil water content content and restrictive values to root growth were found only when soils were dry.

Several studies were performed in order to establish relations among soil properties and strength, but few of them were performed with undisturbed samples considering no-till system, especially in soils with high clay and oxides content, in tropical areas. Thus, the objective of this paper was to study relations among soil physical and mechanical properties in a long-term experiment with different soil tillage systems and nutrient sources applied in an Oxisol located in southern Brazil, under subtropical climate (Cfb – Koeppen).

3.4 Material and methods

3.4.1 Experimental design and treatments

The experiment was carried out since 1994 at the Epagri Experimental Station of Campos Novos/Santa Catarina, Brazil (27^{o}24’S, 51^{o}13’W, 970 m.a.s.l.), on a Typic Haplorthox, a Nitossolo Vermelho in brazilian classification (EMBRAPA, 1999), with high clay, medium organic matter, and high base saturation at soil surface (Table 3.1).

The field and laboratory analysis were performed during the 10th year of the experiment running. Before the experiment installation, the field was used for crop production for more than 20 years, under conventional tillage system (primary disking plow plus two secondary disking). The main treatments are a combination of residue management and soil tillage, but only those treatments where residues were maintained in the field (on the surface/no-till, semi-incorporated/chisel plow, and incorporated/conventional tillage) were analysed in this paper. The secondary treatments are nutrient sources used by the farmers locally (mineral fertilizer, poultry litter, slurry swine manure and slurry cattle manure) and without fertilizers (control). The experimental design corresponds to subdivided random blocks with three replications, with the tillage treatments and nutrients sources as variables.

The crops were seeding in a three-year crop rotation, including crops for grain production in spring/summer season and cover crops in autumn/winter season, according to the sequence: triticale or rye/soybean/common vetch/corn/black oat/black bean. A tractor with approximately 4.0 Mg and four-wheel drive was used to perform the primary tillage operations (i.e. primary disking plow and chisel plow) and a tractor with approximately 2.9 Mg and two–wheel drive was used to perform the secondary tillage operations (i.e. secondary disking) and seeding. Only soybean and triticale were harvested with a combine harvester with mass of about 10 Mg.

Table 3.1 - General physical and chemical characterization of the analyzed soil profile at experimental site at the beginning of the experiment.

Horizon	Depth	Clay	Silt	Sand	OC	pH	S	T
	cm	------------------- % --------------------					-- $cmol_c\ L^{-1}$ --	
Ap	0 – 23	70.5	27.1	2.4	1.84	7.0	13.18	14.28
BA	23 – 38	74.5	24.2	1.3	1.55	6.4	8.65	11.95
Bt1	38 – 62	82.0	17.7	0.8	1.26	5.3	2.23	12.73
Bt2	62 – 88	82.0	17.5	0.4	0.86	5.3	1.83	10.63
Bw	88 – 134+	76.7	22.4	0.9	0.40	4.9	0.53	10.13

OC = organic carbon; S = sum of basic cations; T = cation exchange capacity at pH 7.

3.4.2 Soil compressibility

Stress strain curves were determined using undisturbed samples (10 cm diameter and 3 cm height), at two depths: 5 (3.5-6.5 cm layer) and 15 cm (13.5-16.5 cm layer), collected in the untrafficked interrow of poultry litter and mineral fertilizer treatments, six months after last tillage in 2003. Samples were saturated and equilibrated at -60 hPa pore water pressure on sand boxes. The compressibility test was performed under confined conditions in a multi-step apparatus with normal loads of 10, 20, 30, 50, 80, 120, 200, 300 and 400 kPa. Height changes and changes in pore water pressure were recorded automatically. Each load was applied either for 30 or 120 minutes before the following load was added. In order to determine the effect of soil aggregation on soil compressibility also remolded samples were equilibrated at – 60 and – 300 hPa pore water pressure and thereafter load for 30 minutes each with identical normal loads as previously described.

The precompression stress value, which defines the transition from the reloading curve to the virgin compression line (or the highest load previously supported by the soil), was calculated mathematically using parameters of van Genuchten equation originally developed for soil water retention curve, but modified by Baumgartl & Kock (2004) for the mechanical analysis. Effective stress at the end of each load applied was calculated using Eq. 3.3, considering the ? factor identical to the saturation degree, since the values of saturation degree were always higher than 60 % at the beginning of the test. Additionally the compressibility coefficient was calculated using two points of the virgin compression line, using the relation ?*vr*/? log*s* ’, where *vr* is the void ratio and *s* ’ the effective stress.

3.4.3 Penetration resistance

Cone index was determined under in situ conditions one week after seeding and 3-5 days after a rainfall, when the soil water content was nearly field capacity, using a digital handheld cone penetrometer (30^{o} cone tip angle, 10 mm diameter). Measurements were taken in increments of 1.5 cm until 60 cm depth with a penetration velocity of about 1 m min^{-1}. This determination was performed in all nutrient sources treatments at three positions in each plot: at seeding row (SR), at untrafficked interrow (UI), and at recently trafficked interrow (TI). The recent traffic corresponded to two passes of the tractor of about 2.9 Mg during the seeding procedure. Due to soil surface irregularity in the field, statistical analysis of penetration resistance was performed using average values of three depths increments, plotted in the middle point.

3.4.4 Statistical analysis

Statistical analysis were performed using the Statistical Analysis System (SAS, 1989), and include ANOVA test for physical and mechanical analysis for variances among soil tillage, nutrient sources and depth. Means differences were compared using the Tukey test (P<0.05).

3.5 Results and discussion

There were statistical differences among tillage systems and between depths for all physical and mechanical parameters analyzed (Table 3.2). Precompression stress was the only one which showed statistical differences between nutrient sources, without interaction between tillage and depth. The time interval of 30 and 120 min between loads did not affect significantly mechanical parameters determined in the compressibility test.

Table 3.2 - Analysis of variance (ANOVA) for soil physical and mechanical parameters determined in undisturbed samples collected in three soil tillage systems, two nutrient sources and two depths, equilibrated at – 60 hPa suction.

Sources of variation	BD	TP	S60	S_p	C_c	R%
Soil tillage (ST)	**	**	**	**	**	**
Nutrient source (NS)	ns	ns	ns	**	ns	ns
ST*NS	ns	ns	ns	ns	ns	ns
Depth	**	**	**	**	**	**
ST*depth	**	**	**	ns	**	*
Load time				ns	ns	ns

BD = bulk density; TP = total porosity; S60 = saturation degree at -60 hPa suction; S_p = precompression stress; C_c = compressibility coeficient; R% = percent of rebound related to original settlement.
** P < 0.01; * P < 0.05; ns = no significante.

Greater differences in physical parameters were observed for the upper layer (Table 3.3). No-till showed the greatest bulk density at sampling time and, consequently, lower total porosity and higher microporosity, as showed by the higher saturation degree at -60 hPa. The same trend was observed at 15 cm depth, but statistical differences were observed only for bulk density. These results are in agreement with those obtained in other studies (Hubbard et al., 1994; Derpsch et al., 1991; Fernandes et al., 1983) and are due to the fact that, in no-till system, only part of soil surface is disturbed at seeding row, and interrow remain identical to the former period. In this case, the balance between cumulative load applied and natural tendency to realleviate them was favorable to soil compaction. For tillage treatments, soil is mobilized to the plowing depth and remains “looser” until the application of a higher load than the new soil strength state. The time interval between tillage and soil sampling was not long enough to promote natural soil settlement due to wetting and drying cycles that could eliminate this effect.

Table 3.3 - Statistical analysis of soil physical and mechanical parameters in undisturbed samples collected in two depths of three soil managements systems.

Depth	Soil tillage	BD	TP	S60	C_c	R
		g cm^{-3}	------ cm^3 cm^{-3} ------			%
5 cm	No-till	1.19 a	0.52 b	0.85 a	- 0.27 a	33.3 a
	Chisel plow	1.02 b	0.59 a	0.66 b	- 0.50 b	19.4 b
	Conventional tillage	1.03 b	0.59 a	0.67 b	- 0.47 b	18.6 b
15 cm	No-till	1.23 a	0.51 a	0.86 a	- 0.24 a	34.4 a
	Chisel plow	1.17 ab	0.54 a	0.83 a	- 0.31 ab	27.3 b
	Conventional tillage	1.16 b	0.54 a	0.83 a	- 0.32 b	26.7 b

BD = bulk density; TP = total porosity; S60 = saturation degree at -60 hPa suction; C_c = compressibility coeficient; R% = percent of rebound related to final settlement;
Means followed by the same letter in a given column in each depth are not statistically different (Tukey, $P < 0.05$).

Soil mechanical parameters are directly related to bulk density or state of compaction. The higher the bulk density, the higher the precompression stress and the percent rebound, and the lower is the compressibility coefficient (Tables 3.3 and 3.4). After ten years of different treatments and six months after the last tillage, no-till showed greater soil strength at both depths compared with the tilled sites. This behavior can be explained by the smaller proportion of soil mobilization in the no-till plot which results in natural soil strength increase and soil compaction due to the previous machinery traffic. The greater precompression stress observed in the no-till system caused greater soil strength and smaller additional plastic deformation, as can be confirmed by the higher percent rebound and lower compressibility coefficient observed in this treatment. These results are in agreement with those obtained by Horn (2004), who determined that soil strength in conservation tillage system increased with time and can be observed even in deeper layers. Less differences were observed among soil tillage treatments when the compressibility test was performed with remolded samples (Table 3.5), suggesting that remolding eliminated partially the effect of direct strength increase due to soil aggregation, which, in turn, imply increased σ_p of about four times. The latter is an important fact as is well known that soil physical degradation clearly reduces aggregation.

The application of poultry litter compared to mineral fertilizer resulted in lower precompression stress. This behavior can be explained by the effect of organic matter in some physical properties, reducing soil consistence in soils with high clay content, since about 3 Mg of additional dry-organic material was applied annually in this treatment. Soil organic matter reduces the susceptibility of soil to compaction (Cc value) and soil with lower previous compaction state (lower bulk density and strength) usually showed lower precompression stress values (σ_p values) (Braida, 2004). No differences in precompression stress were observed between nutrient sources in remolded samples, suggesting that the effect is greater in macro than in microaggregation.

Table 3.4 - Precompression stress of undisturbed samples collected in two depths of the three soil tillage systems and two nutrient sources, equilibrated at -60 hPa suction.

Treatment	Precompression stress		
	5 cm	15 cm	Average
	------------------------------ kPa ------------------------------		
Soil tillage			
No-till	76	105	90 a
Chisel plow	54	78	66 b
Conventional tillage	55	88	71 b
Nutrient source			
Mineral fertilizer	68	98	83 a
Poultry litter	55	82	68 b
Average	61 b	90 a	

Means followed by the same letter in a given column or row are not statistically different (Tukey, P < 0.05).

Table 3.5 - Precompression stress in remolded samples collected in three soil tillage systems (average of two nutrient sources), equilibrated at -60 hPa and – 300 hPa suction.

	Precompression stress		
	-60 kPa	-300 kPa	Average
	------------------------------ kPa ------------------------------		
Soil tillage			
No-till	19	52	35 a
Chisel plow	17	43	30 a
Conventional tillage	17	48	32 a
Average	18 b	48 a	

Means followed by the same letter in a given column or row are not statistically different (Tukey, P < 0.05).

Soil tillage systems showed different behaviors in terms of settlement and pore water pressure changes during the compressibility test (Figure 3.1). At 5 cm depth, conventional tillage and the chisel plow system presented much higher void ratio values at the small applied stresses on the elastic deformation curve, due to the smaller bulk density, but the void ratio values reduced drastically after the precompression stress was exceeded (i.e. in the virgin compression load range). Differences between the two soil tillage systems were smaller at 15 cm depth, but showed the same trend.

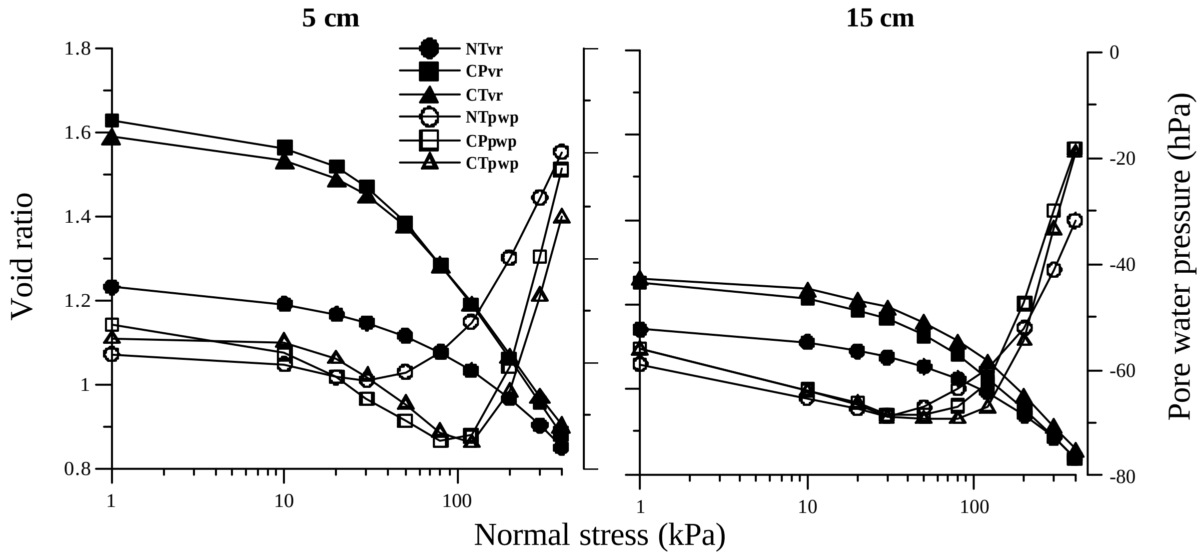

Figure 3.1 - Void ratio and pore water pressure changes as a result of applied sequential stresses (multistep) in undisturbed samples collected at two depths of three soil managements systems (averaged across time intervals) and equilibrated at -60 hPa suction; NT = no-till; CP = chisel plow; CT = conventional tillage; vr = void ratio and; pwp = pore water pressure.

Pore water pressure started almost at the same value for all tillage systems and sampled depths, but showed different behavior during the test. In no-till system, pore water pressure became only a little more negative at the beginning and increased if normal stress greater than 30 kPa were applied. This behavior can be explained by the low soil deformation in this system (higher strain), and pore size distribution remained almost the same wit low stress applied. In tilled treatments, pore water pressure became much more negative at 5 cm depth and increased only after 100 kPa normal stress. At 15 cm depth there were only small differences in pore water pressure among the tillage treatments. These differences are related to the soil deformation dependent rearrangement of the pore size distribution due to applied stress, which includes a reduction of macropores and increase in mesopores. This reduction in pore water pressure is more pronounced with increasing time of loading (Figure 3.2), since this time allows a more complete water redistribution inside the whole sample. The readings by the tensiometer at the bottom of the stressed soil sample give only the average of changes in the pore water pressure value inside the whole soil sample. We can not define the maximum pore water pressure changes near the stress plate nor can we differentiate the height dependent changes in the hydraulic conductivity inside the soil sample at present.

A similar relationship between loading time and pore water pressure was obtained by Fazekas & Horn (2005) in remolded samples with a given initial bulk density of 1.4 g cm^{-3}, and an initial pore water pressure of -60 hPa suction. They showed that the differences were the greater the longer the samples were stressed (from 10 up to 240 minutes). In the present study 30 minutes time interval between loads was not long enough to reach complete water redistribution inside the whole sample after soil deformation, since by applying 120 minutes the curves changed significantly. The corresponding changes as a function of loading time and stress applied reveal pronounced differences especially at 5 cm depth in between the various treatments (Figure 3.3). These changes, however, did not result in statistically significant differences in soil mechanical parameters determined in the compressibility test.

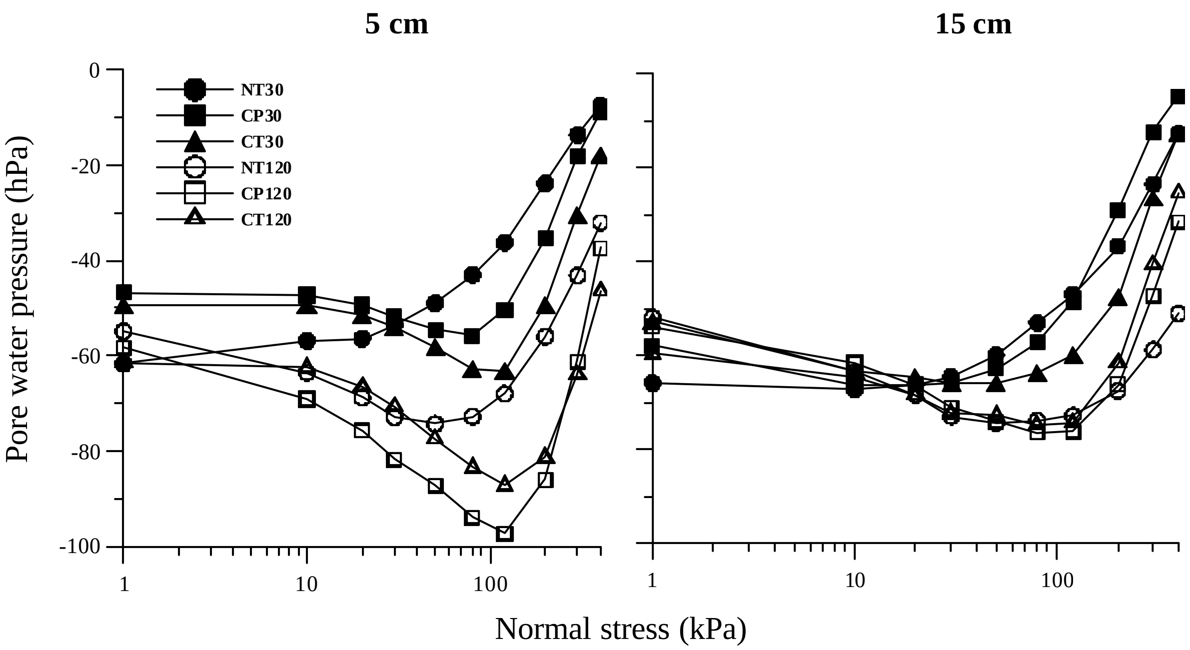

Figure 3.2 - Pore water pressure at the end of each sequential load applied in two time intervals (30 and 120 min) in a multistep device, using undisturbed samples collected at two depths of three soil managements systems and equilibrated at -60 hPa suction. NT = no-till; CP = chisel plow and; CT = conventional tillage.

Cone penetrometer resistance profiles determined at three positions showed treatment dependent strength differences (Figure 3.3). Penetration resistance in any position or depth was not greater than 2 MPa for the soil water content conditions at the time of penetration resistance determination, showing that, if light machinery is used to perform tillage and seeding operations, it is not expected formation of compacted layers with strength higher than root penetration ability (Taylor et al, 1966; Tavares et al., 2001). In no-till system, there were statistically significant differences among positions only in the upper 10 to 12 cm layer, because the small chisel used in planter to open the seeding furrow promoted soil mobilization and reduced the penetration resistance. Below 15 cm, all sampled positions showed the same resistance. Recent traffic promoted additional compaction in a thin, surface layer (< 5 cm). Chisel plow showed greater penetration resistance values at the recently trafficked interrow down to deeper layers (40 cm), as a result of two passes of a light tractor (4 Mg). The conventional tillage (primary plus two secondary disking), on the other hand, resulted in greatest strength at about 20 cm depth (plow pan layer), which now results in a more pronounced stress attenuation and a protection of deeper soil horizons as long as the maximum stress applied is not further increased by heavier machines.

The deeper effect of traffic on soil strength observed in chisel plow treatment can be due both to the absence of surface layer with higher soil strength to avoid stress transmition to deeper layers, and to the higher concentration factor (v) observed in soils with smaller mechanical strength (Horn, 1995). The concentration factor determines the vertical stress distribution along a vertical line under the tire center and, at a given pore water pressure, the greater the factor v, the narrower and deeper the distribution of stress isolines along the vertical line (Soehne, 1958).

Analyzing the soil tillage systems for each sampled position, the lower penetration resistance values were found at seeding row and untrafficked interrow (Figure 3.4). At seeding row, chisel plowed soil had lower penetration resistance than the other systems, in the layer from 15 to 25 cm. No-till showed higher cone penetrometer resistance down to 40 cm depth at untrafficked interrow. Since the gravimetric water content was similar among tillage treatments in depths sampled at time of the penetration resistance determination (Figure 3.5), higher soil strength might be related to differences in bulk density (Figure 3.5) in upper layers, but not near 30 cm depth, where bulk density was similar among tillage treatments and cone penetrometer resistance were higher at untrafficked interrow in no-till treatment.

The higher soil strength in surface layer can be related to traffic history in the last ten years of no-till treatment, while in deeper layers the greater values can be explained by residual effect of previous tillage systems. At recently trafficked interrow, there is a statistically significant difference only at approximately 10 cm depth, showing that irrespective of the present soil strength after plowing, the present stress application always results in an additional soil deformation because the stresses applied exceed the internal soil strength defined as precompression stress.

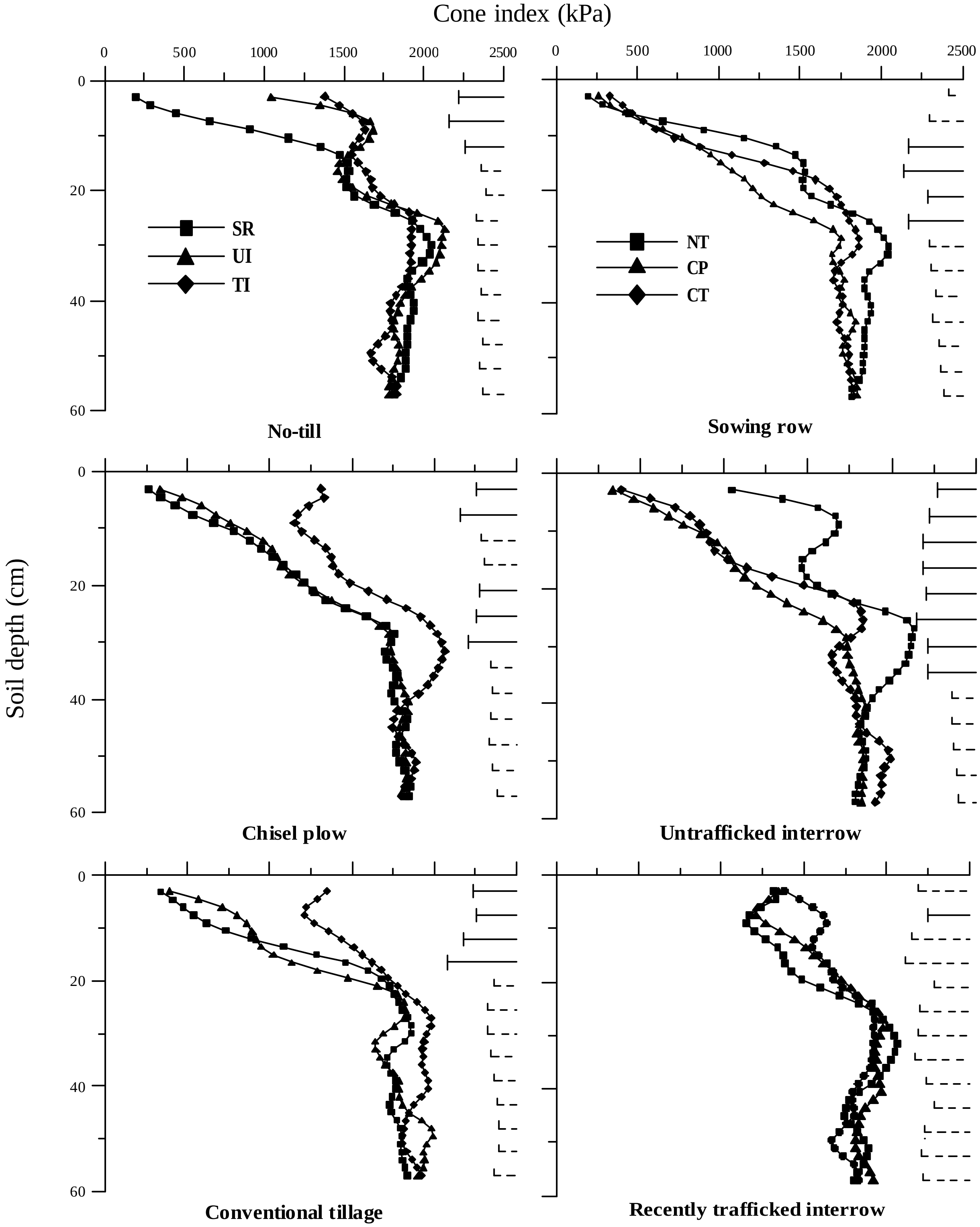

Figure 3.3 - Cone penetrometer resistance profiles determined one week after seeding in three soil tillage systems and three row positions (NT = no-till; CP = chisel plow; CT = conventional tillage; SR = seeding row; UI = untrafficked interrow; and TI = recently trafficked interrow). Horizontal bars indicate least significant difference values (Tukey test); continuous bars indicate differences at P < 0.05.

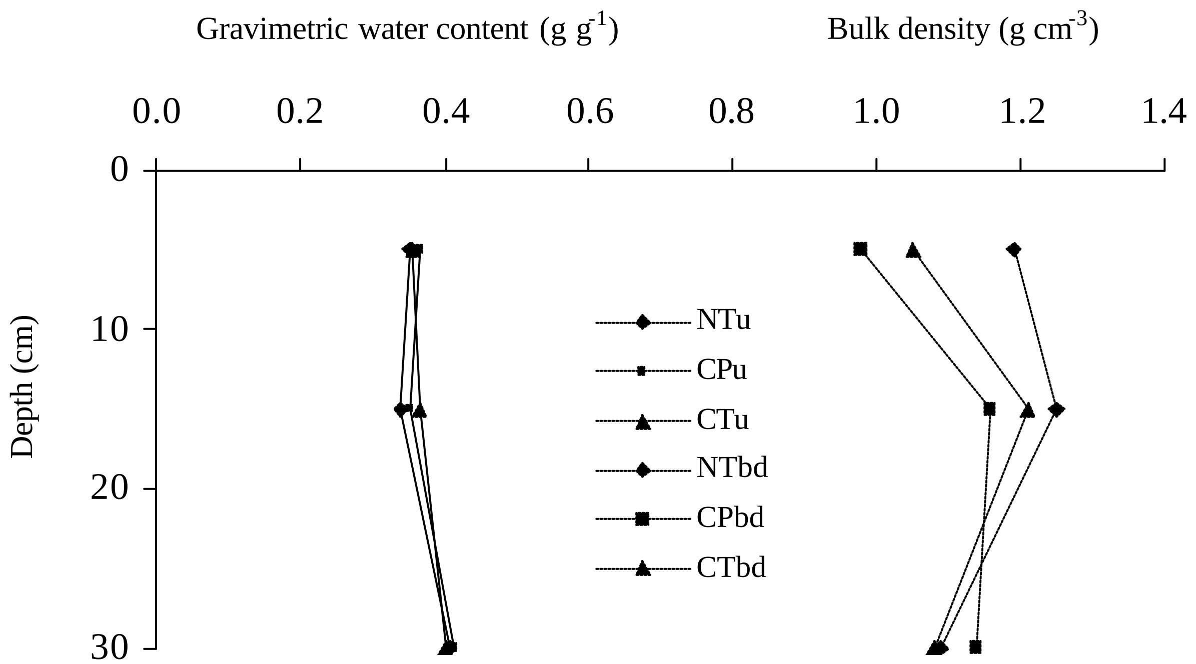

Figure 3.5 - Gravimetric water content and bulk density at three depths of three tillage systems in samples collected in untrafficked interrow at time of the penetration resistance determination. (NT = no-till; CP = chisel plow; CT = conventional tillage; u = gravimetric water content; and bd = bulk density).

The results confirm the necessity of avoiding traffic after plowing the soil in order to avoid the recreation of former strength condition, or even higher and deeper. On the other hand, superficial compacted layer created by traffic of light machinery in no-till system can be easily realleviated at seeding row if seeding machine has appropriate apparatus to cut the soil until depth below this layer.

3.6 Conclusions

No-till system showed higher soil resistance to deformation, as determined by the compressibility parameters and penetration resistance, at both depths (5 and 15 cm).

The original soil structure was responsible for soil bearing capacity around four times higher as compared to soil with remolded structure.

The addition of extra organic matter (poultry litter) resulted in reduced precompression stress values in undisturbed samples and higher compression index and elasticity (rebound).

The precompression stress, compressibility coefficient and penetration resistance were related to bulk density;

Penetration resistance profile was a good indicator of spatial variation in soil strength, both horizontally (seeding row, untrafficked interrow and recently trafficked interrow) and vertically (different soil depths).

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CAPITULO 4. EFEITO DE SISTEMAS DE PREPARO DO SOLO E FONTES DE NUTRIENTES SOBRE A COBERTURA, TEMPERATURA E UMIDADE DO SOLO DURANTE UM CICLO DA CULTURA DE MILHO

4.1 Resumo

A temperatura e a umidade do solo são fatores determinantes para a produção de culturas em função de seu efeito sobre o crescimento e desenvolvimento das mesmas. Os regimes de temperatura e de umidade do solo são afetados pelos sistemas de preparo porque eles resultam em diferentes condições de cobertura após as operações ou porque afetam as propriedades físicas do solo, como a densidade e a distribuição de diâmetro de poros. Este estudo foi efetuado para determinar as relações entre o preparo, cobertura, temperatura e umidade do solo durante um ciclo da cultura de milho, após longo prazo de aplicação de cinco sistemas de preparo do solo (PD = plantio direto; PE = escarificação + gradagem; PC = aração + 2 gradagens; PCq = PC com resíduos queimados e; PCr = PC com resíduos retirados) associados a cinco fontes de nutrientes (T = testemunha; AM = adubação mineral de acordo com a recomendação para manutenção de cada cultura; EA = 5 Mg ha^{-1} a^{-1} de cama de aviário, base úmida; EB = 60 m^3 ha^{-1} a^{-1} de esterco líquido de bovinos e; 40 m^3 ha^{-1} a^{-1} de esterco líquido de suínos). A cobertura do solo após a semeadura foi maior no PD (88%), intermediária no PE (38%) e menor no PC (< 10%) e as diferenças reduziram após a emergência do milho em função crescimento deste. A temperatura do solo foi significativamente influenciada pela cobertura do solo e as maiores diferenças entre sistemas de preparo foram observadas no início do ciclo da cultura. O PD apresentou a menor temperatura diária e amplitude de variação, seguido pelo PE. As maiores diferenças entre PD e PC em um determinado dia foram 8,8, 5,1 e 3,0 ºC, determinadas respectivamente nas profundidades de 2,5, 5 e 10 cm. Em função da elevada e relativamente bem distribuída precipitação pluviométrica no período entre a semeadura e o início do florescimento, diferenças em umidade volumétrica foram observadas somente a 5 cm de profundidade. Nesta profundidade o PE apresentou redução mais rápida na umidade volumétrica na camada superficial (0-23 cm), sendo que valores mais altos foram observados no PD e intermediários no PC. A mesma tendência foi observada a 5 cm de profundidade, mas diferente a 15 cm. Nesta profundidade, menor umidade volumétrica foi observada no PC, intermediária no PD e maior no PE, principalmente no período mais seco (após florescimento do milho). Menor variação na umidade volumétrica foi observada na camada mais profunda (23-46 cm) ou entre fontes de nutrientes.

Palavras chaves: preparo do solo, umidade do solo, temperatura do solo, cobertura do solo, estercos.

SOIL TILLAGE SYSTEMS AND NUTRIENT SOURCES AS AFFECTING SOIL COVER, TEMPERATURE AND MOISTURE, THROUGHOUT A CORN CYCLE

4.2 Abstract

Soil temperature and moisture are determining factors in plant production because of their effect on plant growth and development. Soil temperature and moisture regimes are affected by tillage systems because they leave different amounts of mulch on the soil surface or because they affect soil physical properties such as bulk density and pore size distribution. This study was performed in order to determine relations among soil tillage, cover, temperature and moisture during a corn growing season, after long-term use of five soil tillage systems (NT = no-till; CP = chisel plow + 1 secondary disking; CT = primary + 2 secondary disking; CTb = CT with crop residues burned; and CTr = CT with crop residues removed from the field) associated with five nutrient sources (C = control, without nutrient application; MF = mineral fertilizers according official recommendation for each crop; PL = 5 Mg ha^{-1} y^{-1} of wet matter of poultry litter; CM = 60 m^3 ha^{-1} y^{-1} of slurry cattle manure; and SM = 40 m^3 ha^{-1} y^{-1} of slurry swine manure). Soil cover after seeding was greater in NT (88%), intermediate in CP (38%) and lesser in CT treatments (< 10%). Differences reduced after corn emergence because of the growth of corn leaves and were the least at the last measuring time (54 days after emergence). Soil temperature was strongly related to soil cover and greater differences among tillage treatments were observed at the beginning of the growing season. Lower daily temperature and amplitude of variation were found in NT system, followed by CP. Maximum differences between NT and CT at a given day were 8.8, 5.1 and 3.0 ºC, found respectively for 2.5, 5 and 10 cm depth. Because of high and relatively well distributed rainfall from seeding time to beginning of flowering, differences in volumetric water content were observed only at 5 cm depth, where CP showed faster reduction in volumetric water content after rainfall events. After flowering, when a drier period started, volumetric water content reduced drastically at upper layer (0-23 cm), and higher values were found in NT, followed by CT system. The same trend was observed at 5 cm depth, but different at 15 cm depth. At this depth, lower volumetric water content was found at CT, intermediate in NT and higher in CP, mainly in dryer period. Less variation in volumetric water content was observed at deeper layer (23-46 cm) or among nutrient source treatments.

Keywords: Soil tillage, manure, soil moisture, soil temperature, soil cover.

4.3 Introduction

Soil temperature is a determining factor in plant production because of its effect on plant growth and development, both directly (seed germination, plant emergence, root growth, nutrient uptake, and plant development) and indirectly (through its effect on soil water, aeration, nutrient availability and decomposition of plant residues). The range of optimal soil temperatures for crop production is narrow and, at the same time as crop can not be grown unless soil temperature is above a minimum level, there is an upper limit above that crops can not grow, and different strategies need to be used to avoid both extremes in order to rise crop production (Wierenga et al., 1982).

Soil temperature regime is affected by tillage systems because they leave different amounts of mulch on the soil surface or because they affect soil physical properties such as porosity and water content. Changes in percentage of surface residues cover have greater influence on soil temperature and soil heat inputs than changes in soil thermal properties (Potter et al., 1985), because of reduction in total heat inputs to the soil profile (Johson & Lowery, 1985). Bragagnolo & Mielniczuk (1990) found an average reduction of 0.6 to 1.1 ºC Mg^{-1} of wheat straw on maximum daily temperature at 5 cm depth, depending on insolation and soil moisture. On the other hand, the higher thermal conductivity and specific heat in tillage system with low soil disturbance (e.g., no-till system) produce lower soil temperature in the upper profile (Johnson & Lowery, 1985). No-till system, because crop residues are kept on soil surface, had lower maximum temperature and variation throughout cropping season compared to conventional tillage (Salton & Mielniczuk, 1995).

When crops are not present in the field, soil water regime is primarily regulated by water infiltration and evaporation. Infiltration is regulated mainly by pore size distribution and continuity, as well as by structural stability. Evaporation is affected by the energy available to heat and vaporize water, the ease with which the vapor can move away from the soil, and the ease with which water will move to the evaporation surface from within the soil (Linden, 1982).

According to Lemon (1956), there are three phases involved in water evaporation from the soil, and management of crop residues and soil tillage exert influence on first two ones. Starting with wet soil, the first phase is controlled by external conditions (temperature, wind velocity, air humidity, and sunlight intensity) and water flow freely through soil pores, like from surface of free water. The second phase is characterized by the decrease of dryness rate over time and the evaporation rate is not constant, but a linear function of average soil moisture. The third phase is controlled almost exclusively by dry soil surface, when evaporation is slow and constant, and water loss occurs primarily by vapor diffusion.

Confirming this theory to field conditions, Bond & Willis (1970) found that soil without cover lost the most amount of water in five days (first phase), followed by a drastic reduction in evaporation until the tenth day (second phase), when it became constant (third phase). For the same soil, the greater the amount of soil cover by straw, the lesser but constant the daily evaporation rate in first period, and lowering slowly after that. Cumulative evaporation in 65 days period was approximately one third with high amount of straw on the surface (17.9 Mg ha^{-1}) compared to no cover condition. At field conditions, greater wheat straw amount kept on surface (7.5 Mg ha^{-1}) resulted in an average of 8 to 10 percent unit of soil water content above compared to no cover treatment at 0-5 cm layer, due to lower temperature and surface protection promoted by straw (Bragagnolo & Mielniczuk, 1990). This topic assumes greater importance during summer growing crop periods, when transpiration must be also considered. Lesser evaporation in treatment with soil cover allowed greater water absorption and transpiration during vegetative cycle of bean (43 mm higher), resulting in greater grain production (Barros & Hanks, 1993).

No-till system showed higher soil water content compared to conventional tillage, mainly at 0-5 cm layer, resulting in longer period with soil water into available range to crops (Salton & Mielniczuk, 1995). Similar results were found by Sidiras et al (1983), who observed water content at field capacity 4 to 5% unit higher for no-till system than for conventional tillage at 0-20 cm layer. These differences resulted in 36 to 45% higher water availability in no-till system, which can be explained both by greater water infiltration or lesser evaporation, and are due to crop residue kept on the surface. Since water uptake and root elongation increase both because water tension decrease or the water content at the same tension increase, greater crop development and production could be expected in tillage systems with higher water retention at the same suction (Peters, 1957).

Derpsch et al. (1991) showed that, in relatively short periods, no available water was found at 0-20 cm layer in conventional and reduced tillage (chisel plow). On the other hand, in no-till system, water available was found even with larger time intervals without rainfall. These authors concluded that the differences in water availability were determinant to ensure crop production, mainly in short periods without rainfall (3 to 6 weeks), as well as increasing seeding period (resulting in better stand in periods with moisture deficits) and biological activity. No-till system, besides minimizing the effect of short periods without rain, allow cultivation of no irrigated crops in regions with larger periods with low rainfall or even in semi arid places, with short rainy periods and low total rainfall.

Water retention and availability for longer periods without rainfall in different soil tillage systems and tillage practices, however, has been subject of a few studies. Melo Filho & Silva (1993) found greater water content at 25 and 75 cm depth in no-till than in conventional tillage during the first month of growing period, and inverse values after than, when greater water content was found in conventional tillage. The authors associated this behavior to breaking of capillarity continuity promoted by surface soil mobilization in conventional tillage, that result in lowering the evaporation rate compared to no-till, where capillarity continuity was maintained. Because this, crop had higher vegetative grow in no-till at the beginning of period without rain, with greater evapotranspiration rates, and reducing faster water content at the layer explored by roots in this treatment. The possibility of cultivating crops in places with severe water restriction with use of conservation soil management systems was studied by Aase & Pikul (1995) at a long-term trial performed at Great Planes, north USA, with an average of 212 mm rainfall during the growing period. They showed that direct seeding of winter cereals was a better choice than traditional system of that region (which consists of fallow during one cropping season to store water, and seeding in next year) on crop production, water use efficiency, and physical and chemical soils characteristics.

Previous studies of temperature and water retention in tillage systems usually were done at given days during crop cycle, and used destructive sampling for water content determination. This study was performed in order to determine relations between soil cover, soil temperature, and water retention throughout a corn growing season, after long-term use of five soil tillage systems and five nutrient sources.

4.4 Material and Methods

This study was performed at a field experiment carried out since may 1994 at the Epagri Experimental Station of Campos Novos (Campos Novos/SC, Brazil, 27º24'S, 51º13'W, 970 m.a.s.l.) with the objective of studying long-term effects of applying soil tillage and nutrient sources treatments on soil properties and crop production. The soil is a Typic Haplorthox, a Nitossolo Vermelho in Brazilian classification (EMBRAPA, 1999) with high clay, medium organic matter, and high base saturation at soil surface (Table 4.1).

The crops were seeding in a three-year crop rotation, including crops for grain production in spring/summer season and cover crops in autumn/winter season, according to the sequence: triticale or rye/soybean/common vetch/black oat/black bean. At the tenth year, common vetch associated with black oat (respectively, 75 and 25% of recommended population) were seeded in April/2003 and a double hybrid corn (4.5 plants m^{-1}, 0.7 m interrow) in the end of October/2003.

Table 4.1 - General physical and chemical characterization of the analyzed soil profile at experimental site at the beginning of the experiment.

Horizon	Depth	Clay	Silt	Sand	OC	pH	S	T
	cm	-------------------	%	--------------------			-- $cmol_c$ L^{-1} --	
Ap	0 – 23	70.5	27.1	2.4	1.84	7.0	13.18	14.28
BA	23 – 38	74.5	24.2	1.3	1.55	6.4	8.65	11.95
Bt1	38 – 62	82.0	17.7	0.8	1.26	5.3	2.23	12.73
Bt2	62 – 88	82.0	17.5	0.4	0.86	5.3	1.83	10.63
Bw	88 – 134+	76.7	22.4	0.9	0.40	4.9	0.53	10.13

OC = organic carbon; S = sum of basic cations; T = cation exchange capacity at pH 7.

4.4.1 Treatments

The main treatments were a combination of residue management and soil tillage, namelly: (NT) no-till; (CP) chisel plow + 1 secondary disking; (CT) primary + 2 secondary disking; (CTb) CT wit crop residues burned; and (CTr) CT with crop residues removed from the field. They were established annually in plots 6 m wide and 30 m long, transversal to slope, before seeding of spring/summer cash crops. The chisel and the primary disking (in conventional tillage) plowed the soil down to respectively 25 and 15 cm depth. Winter cover crops were seeded in autumn using a direct drilling machine. A tractor with approximately 4.0 Mg and four-wheel drive was used to perform the primary tillage operations (i.e. primary disking and chisel plow) and a tractor with approximately 2.9 Mg and two–wheel drive was used to perform the secondary tillage operations (i.e. secondary disking) and seeding. Only soybean and triticale were harvested with a combine harvester with mass of about 10 Mg.

Nutrient sources treatments consisted of: (C) control, without nutrients application; (MF) mineral fertilizers according to official recommendation for each crop (COMISSÃO DE FERTILIDADE DO SOLO – RS/SC, 1995); (PL) 5 Mg ha^{-1} y^{-1} of wet-matter of poultry litter; (CM) 60 m^3 ha^{-1} y^{-1} of slurry cattle manure; and (SM) 40 m^3 ha^{-1} y^{-1} of slurry swine manure. Nutrient sources were applied just before the summer crops seeding, in plots with 6 m wide and 30 m bng, transversal to soil tillage systems (slope direction), before the secondary tillage.

The experimental design consists of a factorial 5 x 5, with 25 treatment combinations and three replications applied in randomized subdivided blocks, as shown in Appendix A.

4.4.2 Soil cover

Soil cover was determined using digital pictures taken weekly at the first stage of corn growing season (from seeding to 53 days after seeding). After this time, because of corn height, lower accuracy of this determination could be expected and cover determination was not performed. At a computer screen a grid with 10 x 10 rows of small circles (100 circles) was painted over the picture, and soil cover by straw or corn leaves was read. It was considered with cover when more than 50% of the circle was filled by straw or leaf, and the sum of circles with cover corresponded to the percent of soil cover.

4.4.3 Soil temperature

Soil temperature was measured at 5 cm depth at the corn interrow position of all combinations of soil tillage and nutrient sources treatments at block 2 of the experiment (25 plots), and at 2.5 and 10 cm depth in all soil tillage systems of mineral fertilizer source in the same block (5 plots), using mercury glass-thermometers. The reading of soil temperature was made at 3:00 pm, every day with sunny or partially sunny conditions. Readings of soil temperature were also taken hourly, during 25 hours period of a sunny day, 12 days after seeding.

4.4.4 Soil moisture

The determination of instantaneously volumetric water content was performed using a Time Domain Reflectometry device made by Soilmoisture Equipment Corp. (TRASE Systems, 1996). Waveguides connectors with two waveguides of 23 cm long, 0.5 cm diameter and 5 cm away from each other, were introduced perpendicularly into the soil in all plots. At plots with combinations of mineral fertilizers treatment with all soil tillage systems, similar waveguides were introduced horizontally at 5 and 15 cm depth, and perpendicularly from 23 to 46 cm layer. Measurements were performed in intervals of 2 or 3 days and transit time of electromagnetic wave in waveguides (?t) read at laboratory from graphics saved at TDR device. Values of apparent dielectric constant of the soil (Ka) were calculated using the equation:

$$\mathbf{Ka = (c?t/L)^2} \qquad (4.1)$$

Where **c** denotes the velocity of electromagnetic wave emitted (30 x 10^9 cm s^{-1}), **?t** the transit time of electromagnetic wave in waveguides (x 10^{-9} s), and **L** the length of waveguides (cm).

To ensure measurements similar those found in the field, a calibration curve specific for this soil was performed using data of volumetric water content and Ka in a large range of soil water content (Figure 4.1). The polynomial equation resulted from this calibration was used to calculate volumetric water content from Ka determined trough the equation 4.1.

4.4.5 Statistical analysis

Statistical analysis was performed using the Statistical Analysis System software (SAS, 1989). ANOVA test was performed to quantifying variances among soil tillage, and nutrient sources. Means differences were compared using the Tukey test ($P < 0.05$) or least square means (general linear models procedure).

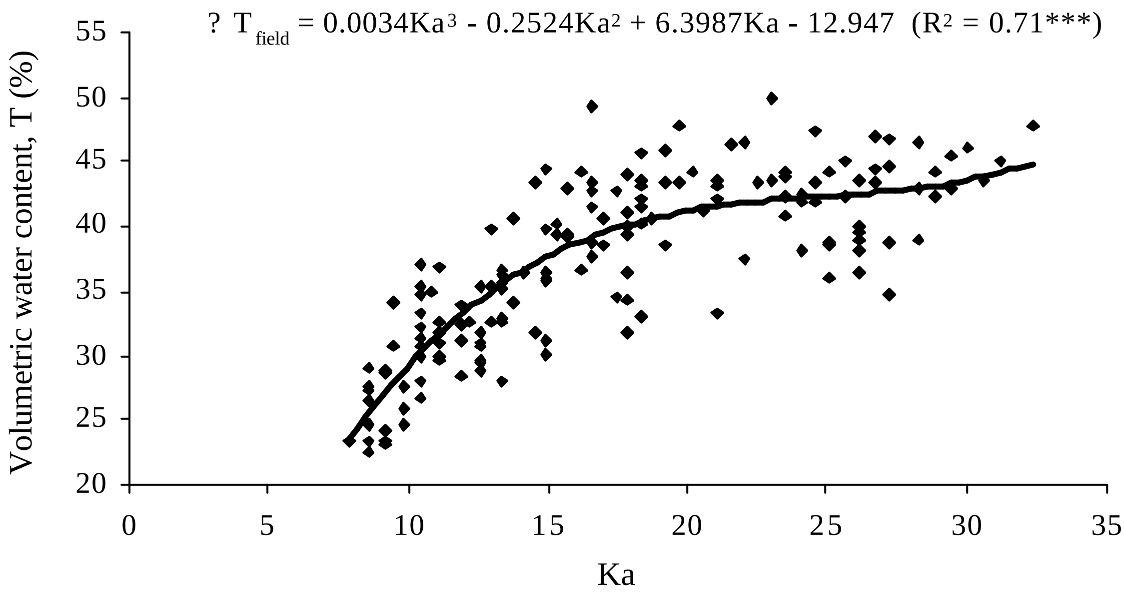

Figure 4.1 - Correlation between apparent dielectric constant of the soil (Ka) with volumetric water content (T) in an Oxisol with high clay content.

4.5 Results and discussion

4.5.1 Soil cover

Soil tillage had a strong effect on soil cover by residues, since tillage operations promoted a partial (chisel plow + 1 secondary disking) and almost total (primary + 2 secondary disking) residue incorporation (Figure 4.2). For no-till system the soil was not covered only at seeding row, where the seeding machine promoted partial residue incorporation. When crop residues were burned or removed from the field, only soil cover by crop leaves was expected.

After corn emergence, soil cover increased in all treatments because of the growth of corn leaves, and differences among treatments reduced over time. Analyzing the trend of soil cover curves, it could be expected that differences would reduce to lower levels at maximum crop development (corn flowering), but could increase again when leaf area index reduce during corn maturation, and residue remaining on the surface determine differences in soil cover among treatments. Soil cover at NT did not rise up to 100% because at the same time as soil cover by leaves was increasing, soil cover by residues was decreasing due to its decomposition. The lower increment in soil cover in CP compared to CT during the time of determination is related to residue decomposition as well as the fact that leaves cover soil both with and without residue cover.

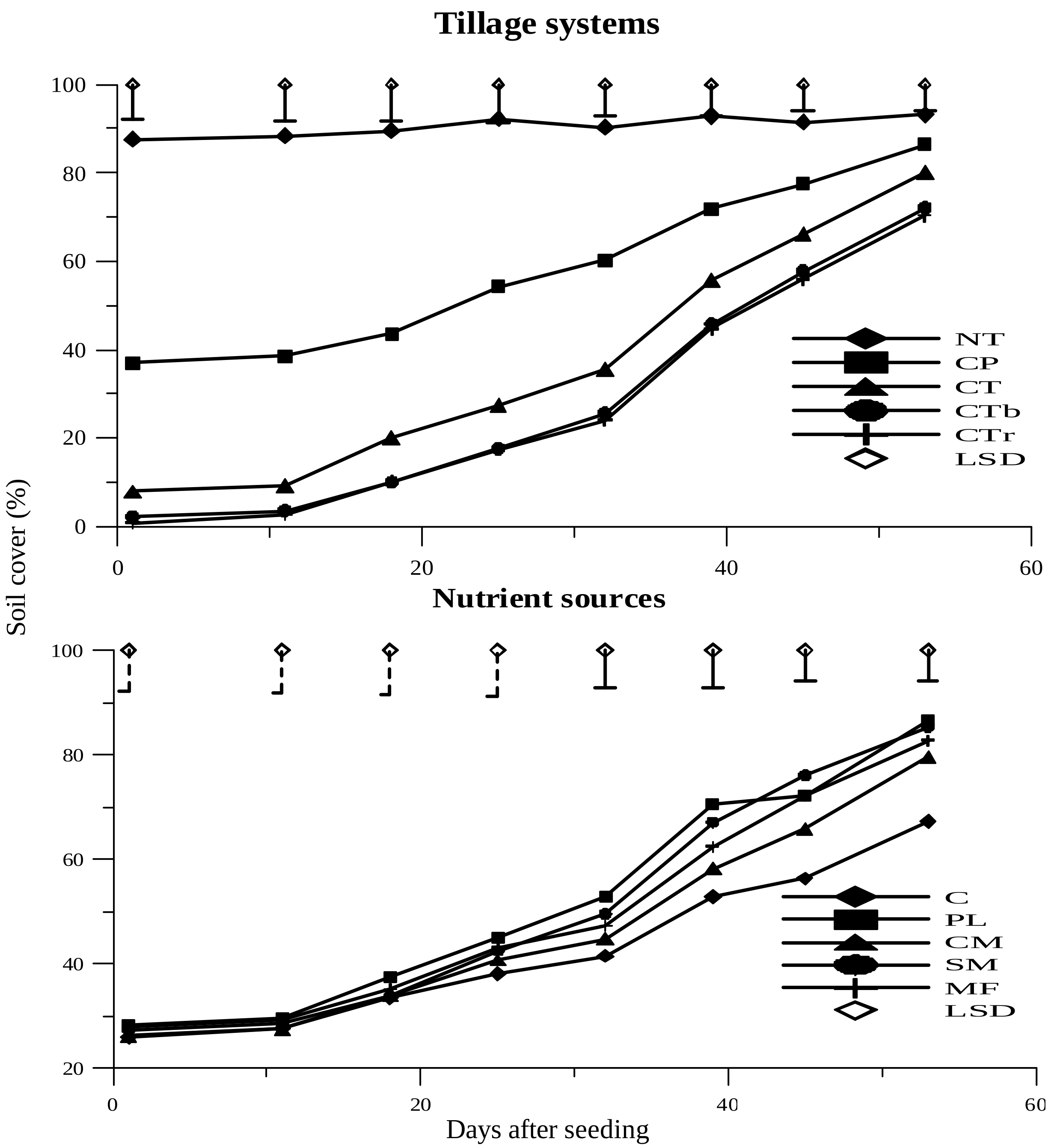

Figure 4.2 - Soil cover by crop residues and corn leaves at first stage of corn growing period in the tenth year, at five soil tillage systems (averaged across nutrient sources) and five nutrient sources (averaged across soil tillage systems). (NT = no-till; CP = chisel plow; CT = conventional tillage; CTb = CT with crop residues burned; CTr = CT with crop residues removed from the field; C = control; PL = poultry litter; CM = cattle manure; SM = swine manure; and MF = mineral fertilizer). Vertical bars indicate least significant difference values (Tukey test); continuous bars indicate differences at $P < 0.05$.

Considering the average of five soil tillage treatments, greater differences in soil cover among nutrient sources treatments were found from 30 days after seeding until the end of measurements. This means that soil cover by crop residues of previous cover crop was similar after tillage operations and differences among treatments were due only to differences in corn development. Control treatment (without applying nutrients) showed lower soil cover, followed by cattle manure treatment, but differences seams to reduce again over time.

4.5.2 Soil temperature

Because of low differences in soil temperature among conventional tillage treatments (CT, CTb and CTr), only results of the soil tillage system where crop residues were kept in the field (NT, CP and CT) will be shown, but all of them were considered when statistical analysis was performed.

Soil temperature variation in a given day (12 days after seeding) showed the same trend at the three depths, but the magnitude and amplitude of variation and time to reach the highest and lowest values were different among them (Figure 4.3). Because of low rate of thermal conductivity of the soil, there was a delay in time to reach the highest temperature at deeper soil layers. These values were found at 2:00, 3:00, and 5:00 pm, respectively at 2.5, 5 and 10 cm depth. Higher differences among treatments were found at this time. Near the surface (2.5 cm depth) there were lower differences between CP and CT than in deeper positions (5 and 10 cm depth), although CP had greater soil cover by residues at time of this determination. The lower heat input in CP resulted of higher residue cover was probably compensated by the lower specific heat in upper layer of this treatment due to the low water content at surface, and reducing heat spent for the evaporation process, despite of reducing thermal conductivity.

Temperature profile considering three depths (2.5, 5 and 10 cm) was lower in NT (33.4, 29.6 and 27.0ºC) compared to CP (42.6, 32.8 and 28.6ºC) and CT (42.2, 34.7 and 30.0ºC), resulting in differences of respectively 8.8, 5.1 and 3.0ºC between NT e CT and 9.2, 3.2 and 1.6ºC between NT and CP. Since a short increase or decrease in the amplitude of soil temperature cause a significant physiological change in the crop response, especially for seed germination and initial root grow, it is expected that large variation in soil temperature as found at emergence time could cause negative effects on crop growth and development.

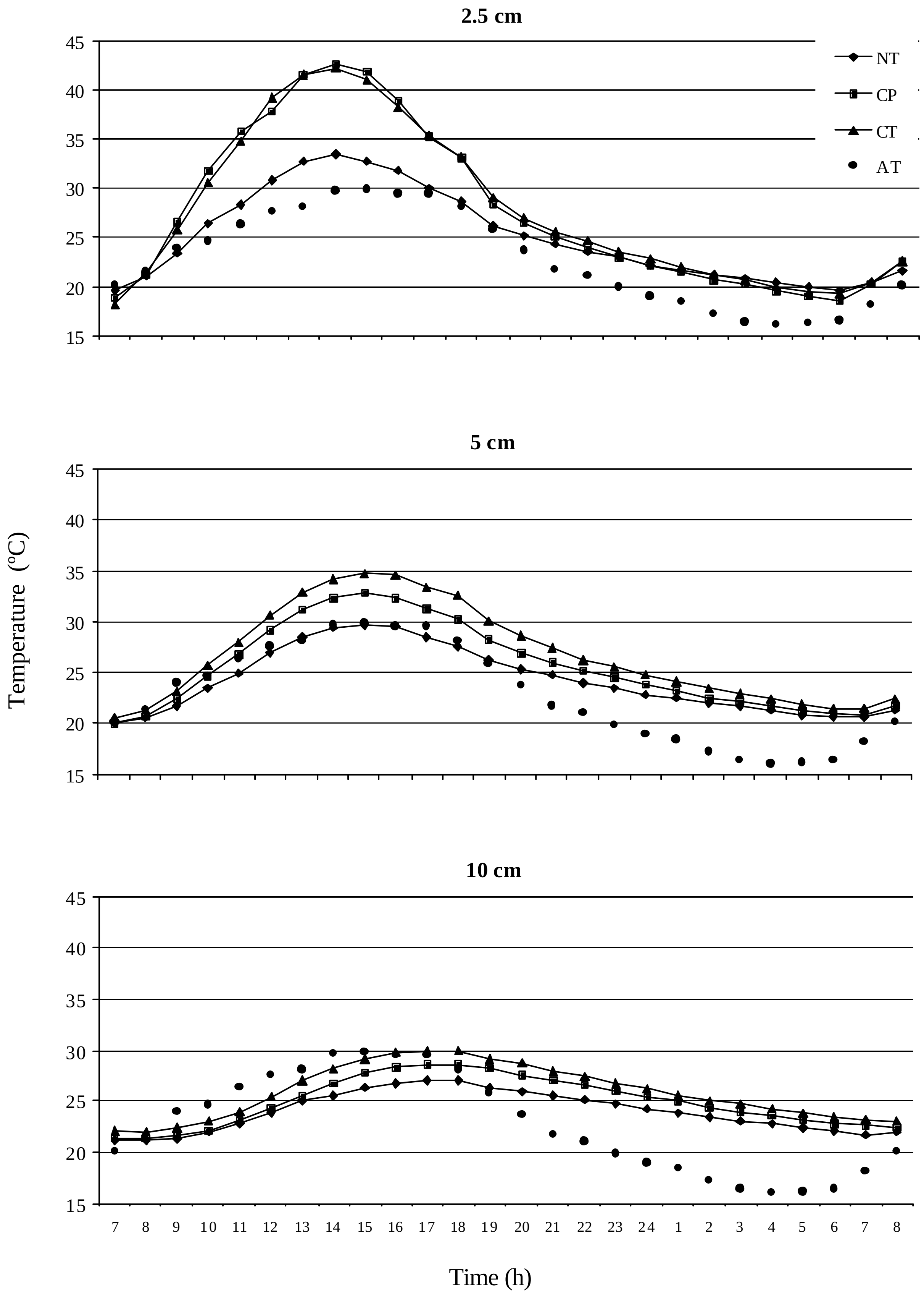

Figure 4.3 – Air temperature and soil temperature at 2.5, 5 and 10 cm depth along one given day (12 days after seeding) in three soil tillage system. (NT = no-till; CP = chisel plow; CT = conventional tillage; AT = air temperature)

Differences in soil temperature among soil tillage systems at 5 cm depth were found from seeding time to around 40 days after seeding (Figure 4.4), when differences in soil cover by residues plus corn leaves was lower (Figure 4.2). Along this period, soil temperature was higher at CT, intermediate at CP and lower at NT treatment. Greater differences among management systems treatments were found at 2.5 cm depth and lesser at 10 cm depth, because of dissipation of heat wave into the soil (Figure 4.3). Differences found from 90 days after seeding onwards are probably due to the reduction in soil cover promoted by corn leaves both because of a hail felt 75 days after seeding (rupturing of leaves) and a severe draught that started after that (death of leaves). At that time, soil cover by residues remained on the surface in NT and CP treatments account for total cover and soil temperature differences among soil tillage treatments.

Air temperature was lower than soil temperature at 2.5 and 5 cm until approximately 60 days after seeding, and switched from that time until the end of corn cycle, being related to crop development and soil cover promoted by corn leaves which avoid direct sunlight incidence on soil surface, reducing total heat inputs. Air temperature was lower than soil temperature at 10 cm depth only at the beginning of crop growth in days with lower air temperature. It needs to be considered that at this depth soil temperature measurement at (3:00 pm) did not coincide with higher soil temperature which is around 5:00 pm.

Among nutrient sources treatments, differences were found from 40 until approximately 90 days after seeding, being related to differences in soil cover due to corn leaves, since crop development showed differences among treatments (Figure 4.4). Despite no statistical differences were found in part of corn cycle, soil temperature at 5 cm depth was lower at poultry litter treatment, followed by swine manure from the beginning to the end of cropping season. The lower soil temperature in these treatments immediately after seeding is related to greater dry-mass production of cover crop cultivated previous to corn, result of cumulative effect of nine years of applying different nutrient sources, although differences in soil cover were not significant at that time. For the same reason, it was not expected that soil temperature in mineral fertilizer treatment could have the highest soil temperature at early growing period and at the end of corn cycle, since the lowest dry-mass of cover crop production was found at control treatment (Chapter 5). Higher soil temperature at control plot was found at period with greater corn vegetative growth, when corn leaves were the main thing in promoting soil cover.

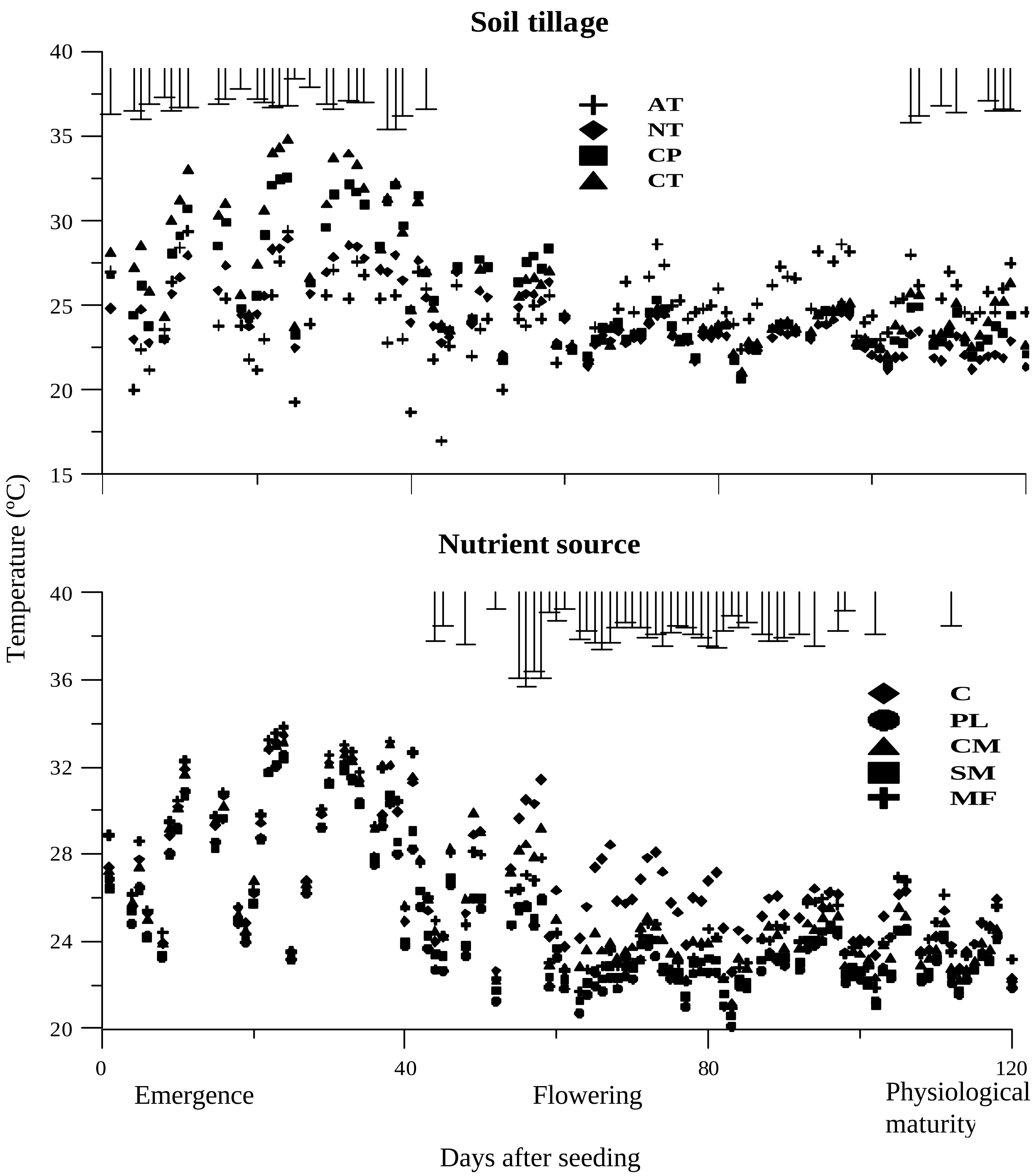

Figure 4.4 – Air temperature and soil temperature at 3 p.m., at 5 cm depth during the corn cycle in three soil tillage systems and five nutrient sources. (AT = air temperature; NT = no-till; CP = chisel plow; CT = conventional tillage; C = control; PL = poultry litter; CM = cattle manure; SM = swine manure; and MF = mineral fertilizer); vertical bars indicate least significant difference values (Tukey, 5%).

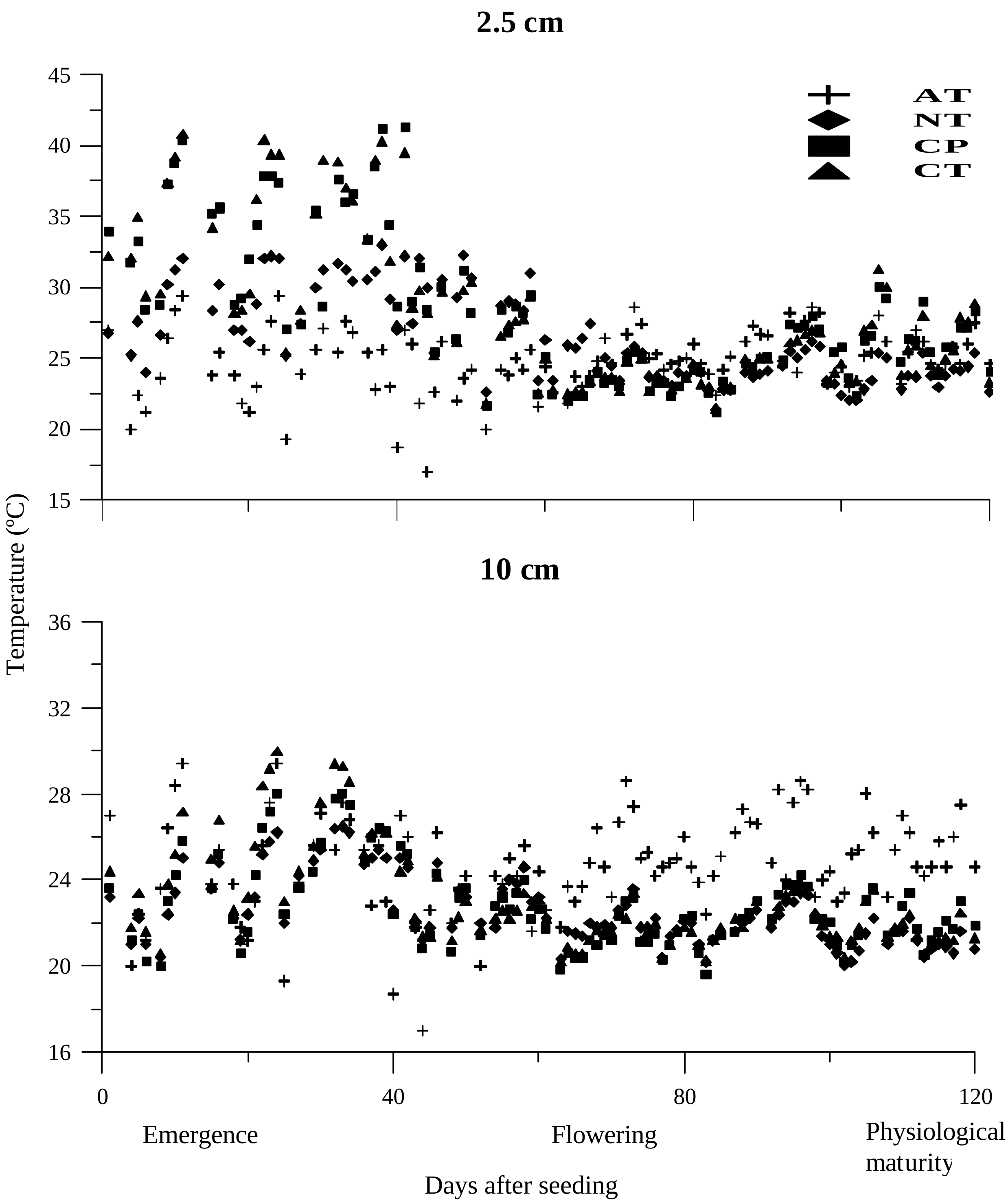

Figure 4.5 – Air temperature and soil temperature at 3 p.m., at 2.5 and 10 cm depth during the corn cycle in three soil tillage systems and five nutrient sources. (AT = air temperature; NT = no-till; CP = chisel plow; and CT = conventional tillage)

4.5.3 Soil moisture

Rainfall was high and relatively well distributed from seeding time to around 80 days after seeding, when the amount was reduced significantly, and volumetric water content at all depths reflected this overall trend (Figures 4.6 and 4.7). At layers of 0-23 and 23-46 cm, volumetric water content remained in nearly constant (values from 40 to 45%) and with little differences among tillage treatments until the beginning of dryer period. In a few days when differences were found among treatments, volumetric water content was lower at CP at 0-23 cm and CT at 23-46 cm layer. During dryer period, volumetric water content decreased continuously and reached higher water tension values (estimated from the water retention curves) at 0-23 cm layer at physiological maturity time (120 DAS). At this layer volumetric water content was higher in NT, intermediate in CT and lower CP. On the other hand, water tension was higher in CT, intermediate in CP and lower in NT. Considering both criteria of water availability to crops (water tension and content), NT showed better conditions in dryer period.

Higher water retention in NT and lower in CP can be explained by the differences in pore size distribution among treatments, since CP showed greater amount of macropores at upper layers during growing season, followed by CT treatment (Chapter 1). Macropores allow for quick drainage of excess of water through the soil profile and do not retain water against gravity. As a result, volumetric water content after rainfall reduced faster in treatments with greater macroporosity and differences remained similar after that. This is confirmed by the behavior of volumetric water content measured at 5 cm depth (average of approximately 0-10 cm layer) at the beginning of cropping cycle, when differences in macroporosity were greater and differences in evaporation rates can not explain alone the high variability in volumetric water content in CP treatment (Figure 4.7). If only evaporation was involved, it would expect lower volumetric water content at CT treatment, where soil cover by residues was lesser, reflecting higher soil temperature at 5 and 10 cm depth. The faster decrease in water content in upper layer for CP treatment resulted capillarity discontinuity and reduced loss of water through evaporation from the intermediate layer, as can be seen at 15 cm depth curves. At this depth, greater water content along almost all growing season was observed at CP and lower at CT treatment.

Differences among nutrient source treatments were found only during dryer period, when treatments with lower crop growth (control and cattle manure) showed higher volumetric water content (Figure 4.8). At this time, loss of water by transpiration was the dominant process and greater crop development resulted in greater water loss by evapotranspiration, and consequently reduced water stored at the upper layer.

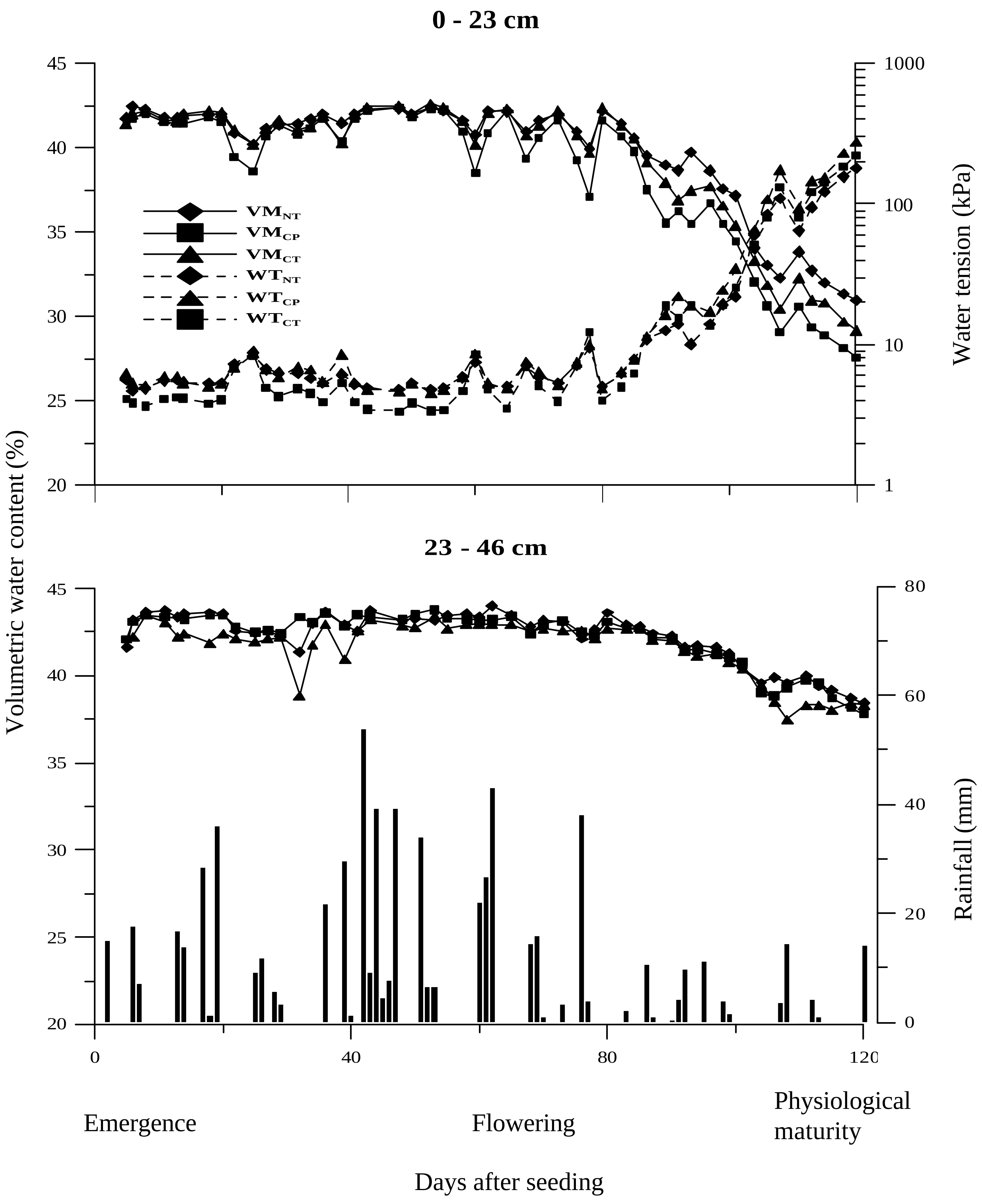

Figure 4.6 - Volumetric water content, estimated water tension, and precipitation (bars) during the corn cycle in three soil tillage systems (averaged across nutrient sources). (VM = volumetric water content; WT = water tension; NT = no-till; CP = chisel plow; CT = conventional tillage)

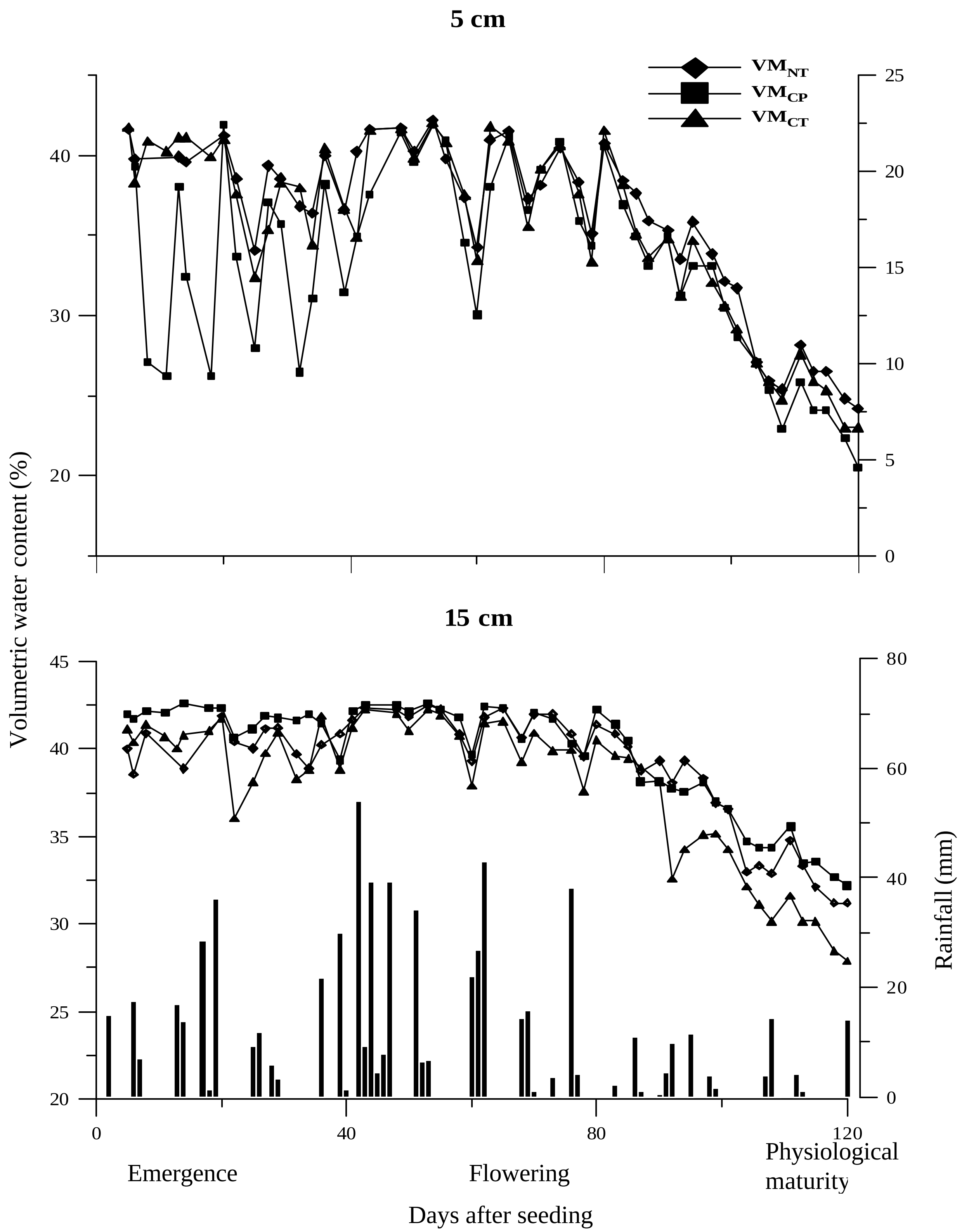

Figure 4.7 - Volumetric water content at 5 and 15 cm depth, and precipitation (bars) during the corn cycle in three soil tillage systems. (VM = volumetric water content; NT = no-till; CP = chisel plow; CT = conventional tillage)

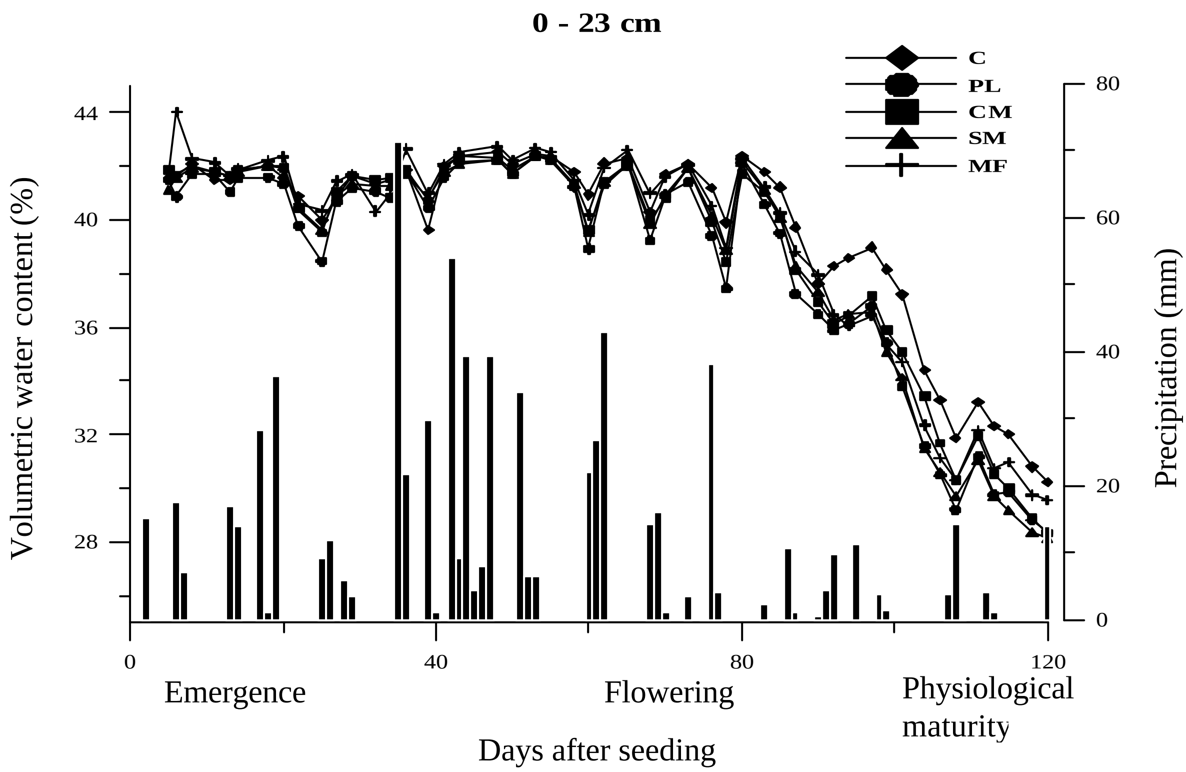

Figure 4.8 - Volumetric water content at 0-23 cm layer and precipitation (bars) during the corn cycle in five nutrient sources (averaged across soil tillage systems). (C = control; PL = poultry litter; CM = cattle manure; SM = swine manure; and MF = mineral fertilizer)

4.6 Conclusions

Soil cover by residues was greater in NT and intermediate in CP immediately after seeding, and differences among tillage treatments reduced over time after corn emergence.

Soil temperature was related to changes in soil cover and greater differences among tillage treatments were observed at the beginning of growing season.

No-till system had lower daily amplitude and maximum temperature at 3:00 pm than tilled treatment. Nutrient sources induced greater differences near flowering, when vegetative growth was different among them.

Temporal variation of volumetric water content was mainly related to soil cover and rainfall distribution. Tillage affected volumetric water content in dryer period, when no-till had greater values.

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CAPITULO 5. EFEITO ACUMULADO DA APLICAÇÃO DE SISTEMAS DE PREPARO E FONTES DE NUTRIENTES SOBRE A FERTILIDADE DO SOLO E O CRESCIMENTO E PRODUÇÃO DE CULTURAS

5.1 Resumo

O objetivo principal do preparo do solo é criar um ambiente favorável para o crescimento e desenvolvimento das culturas e, desta forma, espera-se que o crescimento e produção das culturas sejam afetados pelo preparo do solo. Contudo, os efeitos do preparo sobre as propriedades físicas são dependentes das condições edafoclimáticas e preparos continuados podem ter efeito negativo sobre a qualidade do solo, através da formação de camadas compactadas que podem restringir o crescimento radicular. As propriedades químicas do solo também são afetadas pelo preparo e há uma tendência de aumento da concentração de nutrientes na camada superficial em preparos conservacionistas. Este estudo foi desenvolvido para avaliar o efeito de longo prazo da aplicação de sistemas de preparo do solo (PD = plantio direto; PE = escarificação + gradagem; PC = aração + 2 gradagens; PCq = PC com resíduos queimados e; PCr = PC com resíduos retirados) associados a cinco fontes de nutrientes (T = testemunha; AM = adubação mineral de acordo com a recomendação para manutenção de cada cultura; EA = 5 Mg ha^{-1} a^{-1} de cama de aviário, base úmida; EB = 60 m^3 ha^{-1} a^{-1} de esterco líquido de bovinos e; 40 m^3 ha^{-1} a^{-1} de esterco líquido de suínos) sobre a fertilidade do solo, crescimento e produção das culturas. Os sistemas de preparo do solo e as fontes de nutrientes apresentaram efeito acumulado sobre os parâmetros básicos de fertilidade do solo. Menor fertilidade foi observada no PCr em função da remoção dos resíduos da lavoura. A incorporação parcial dos nutrientes nos tratamentos com preparo do solo (gradagem) resultou em concentração superficial em todos os tratamentos de preparo. Valores mais baixos de P e K no PD do que no PE e PC podem estar relacionados com a perda por escoamento superficial, uma vez que as fontes foram aplicadas superficialmente, sem incorporação. Diferenças acumuladas de fertilidade entre fontes de nutrientes podem ser explicadas pelas diferenças na concentração e nas doses aplicadas. Os sistemas de preparo onde os resíduos foram mantidos na lavoura (PD, PE e PC) apresentaram maior crescimento do milho do que os outros sistemas. O maior crescimento do milho no EA e ES está relacionado ao maior efeito acumulado sobre a fertilidade do solo do que a aplicação por ocasião da semeadura naquele ano. O crescimento das raízes foi maior no PD e PE na camada de 0-10 cm e no PE de 30-40 cm, e não foi observado efeito significativo nas camadas intermediárias ou quando consideradas todas as profundidades amostradas (0-40 cm). A produção de massa seca das culturas de cobertura de inverno e de grãos de milho não apresentou diferenças entre os sistemas onde os resíduos foram mantidos na lavoura. A maior produção de grãos de milho encontrada no PD, apesar de não estatisticamente diferente, pode estar relacionada com a maior retenção de água na camada superficial neste sistema, bem como outras características físicas e biológicas favoráveis, uma vez que a fertilidade do solo era menor no PD do que no PE e PC. O EA e o ES apresentaram a maior produção das culturas, em função do efeito acumulado da aplicação em anos anteriores, já que maiores quantidades de P e K foram aplicados através da adubação mineral na semeadura.

Palavras chaves: preparo do solo, fertilidade do solo, raízes, índice de área foliar, milho.

CUMULATIVE EFFECT OF TILLAGE SYSTEMS AND NUTRIENT SOURCES ON SOIL FERTILITY AND CROP GROWTH AND PRODUCTION

5.2 Abstract

The general purpose of the tillage is to create a soil environment favorable to desired plant growth and development, and it is expected that crop growth and production must be affected by soil tillage. However, tillage effects on soil physical properties are place and seasonal dependent, and continuous long-term cultivation can have detrimental effects on soil quality, creating compacted layer bellow plow layer which can result in restrictions to root growth. Chemical soil properties are also affected by tillage and there is a trend of increasing concentration of nutrients in upper layer in conservation systems. This study was performed in order to evaluate long-term effect of applying soil tillage systems (NT = no-till; CP = chisel plow + 1 secondary disking; CT = primary + 2 secondary disking; CTb = CT with crop residues burned; and CTr = CT with crop residues removed from the field) associated with nutrient sources (C = control, without nutrient application; MF = mineral fertilizers according official recommendation for each crop; PL = 5 Mg ha^{-1} y^{-1} of wet matter of poultry litter; CM = 60 m^3 ha^{-1} y^{-1} of slurry cattle manure; and SM = 40 m^3 ha^{-1} y^{-1} of slurry swine manure) on soil fertility and crop production. Soil tillage and nutrient sources showed cumulative effect on basic soil fertility properties. Lower soil fertility was observed in CTr because residues were removed from the field. Partial incorporation of nutrient sources in tilled treatments resulted in concentration in upper layers of all tillage systems. Lower values of P and K in NT than CP and CT can be due to nutrient loss by runoff, since they were applied on the surface, without incorporation. Cumulative soil fertility differences among nutrient sources treatments are explained by the differences in nutrient concentration and doses applied. Soil tillage where crop residues were kept on the field (NT, CP and CT) showed higher corn growth than others. Greater corn growth in poultry litter and swine manure is related to greater cumulative effect on soil fertility and nutrient application at seeding time. Root growth was greater in NT and CP at 0-10 cm and in CP at 30-40 cm, and no significant effect was found at intermediate layers and when considering the average root density at four depths. Dry-mass production of the winter cover crops and of the corn grain were not different among systems where residues were kept in the field, but greater values were found in NT system, probably because of the greater soil water retention at the upper layer in this system and other favorable physical and biological properties, since soil fertility was lower in NT compared to CP and CT. Poultry litter and swine manure showed higher crop production, mainly because of cumulative soil fertility until the tenth year, since greater amount of P and K were applied at seeding time by mineral fertilizers in that year.

Keywords: soil tillage, soil fertility, root, leaf area index, corn.

5.3 Introduction

Substantial change in soil tillage system use for annual crop production is in course in Brazil lately. No-till system adoption started in seventies, last century, but substantial increase in its utilization occurred from nineties and was used in more than 22 millions hectares in 2003/2004 cropping season, which corresponds to more than half of the total annual cropped area (FEBRAPDP, 2004). The high adoption of this system is related mainly to reduction in costs (Ruedel, 1995) and increase in average crop production, especially in years with low rainfall (Derpsch et al., 1991).

Improvement in water infiltration and high reduction in water and soil loss as a result of conservation soil tillage systems have been shown in several studies performed in different climate and soil conditions (Nunes Filho et al., 1987; Derpsch et al., 1991; Hernani et al., 1997; Beutler et al., 2003). Lower erosion rates were related always to soil tillage systems with low soil disturbance, which leave crop residues on the surface. Soil cover is the isolated factor which has more effect on soil erosion rates reduction (Bertol et al., 1987) and the remaining soil cover after tillage operations is related to the amount of residues before operations and to the type of device and intensity of its use. Surface residues cover appears to be also a dominant factor in determining soil thermal and moisture regimes, minimizing temperature fluctuation and water evaporation (Bragagnolo & Mielniczuk, 1990; Salton & Mielniczuk, 1995; Derpsch et al., 1991).

The general purpose of tillage is to create a soil environment favorable to desired plant growth and development, and it is expected that crop growth and production is affected by soil tillage. Soil tillage generally decreases soil bulk density and increases soil porosity, mainly macroporosity, by loosening up the soil. However, tillage effect on soil physical properties is place and seasonal dependent and reduces over time until reaches the condition before tillage (Ahuja et al., 1998). While annual tillage can temporarily decreases soil compaction at plowed layer, continuous long-term cultivation of land can have detrimental effects on soil quality, creating compacted layer bellow plow layer, which can result in restrictions to root growth (Merten & Mielniczuk, 1991; Ball-Coelho et al., 1998; Silva, 2003). This restriction can be due both because of high penetration resistance when soil is dry (Genro Jr. et al., 2004) or because of reduction in oxygen supply when wet (Chan & Heenan, 1996).

Chemical soil properties are also affected by tillage, and there is a trend of increasing concentration of nutrients in upper layer in conservation systems (Derpsch et al., 1991;

Merten & Mielniczuk, 1991) which can determine root concentration at this layer and reduce crop ability to absorb available water in deeper layers (Merten & Mielniczuk, 1991; Roselem et al., 1992; Ball-Coelho et al., 2004). This process can be increased when nutrient sources are applied on soil surface, without incorporation, like occurs when manures are used in no-till system.

This study was performed in order to evaluate long-term effects of soil tillage systems and nutrient sources on soil fertility and crop growth and production.

5.4 Material and Methods

This study was performed using a field experiment carried out since may 1994 at the Epagri Experimental Station of Campos Novos (Campos Novos/SC, Brazil, 27º24'S, 51º13'W, 970 m.a.s.l.) with the objective of studying long-term effects of applying soil tillage and nutrient sources treatments on soil properties and crop production. The soil is a Typic Haplorthox, a Nitossolo Vermelho in Brazilian classification (EMBRAPA, 1999), with high clay, medium organic matter, and high base saturation at soil surface (Table 5.1).

Table 5.1 - General physical and chemical characterization of the analyzed soil profile at experimental site at the beginning of the experiment.

Horizon	Depth	Clay	Silt	Sand	OC	pH	S	T
	cm	-------------------	%	--------------------			-- $cmol_c\ L^{-1}$ --	
Ap	0 – 23	70.5	27.1	2.4	1.84	7.0	13.18	14.28
BA	23 – 38	74.5	24.2	1.3	1.55	6.4	8.65	11.95
Bt1	38 – 62	82.0	17.7	0.8	1.26	5.3	2.23	12.73
Bt2	62 – 88	82.0	17.5	0.4	0.86	5.3	1.83	10.63
Bw	88 – 134+	76.7	22.4	0.9	0.40	4.9	0.53	10.13

OC = organic carbon; S = sum of basic cations; T = cation exchange capacity at pH 7.

The crops were seeded in a three-year crop rotation, involving crops for grain production in spring/summer season and cover crops in autumn/winter season, according to the sequence: triticale or rye/soybean/common vetch/corn/black oat/black bean. At the tenth year, common vetch associated with black oat (respectively, 75 and 25% of recommended population) were seeded in April/2003 and a double hybrid corn (4.5 plants m^{-1}, 0.7 m interrow) in the end of October/2003.

5.4.1 Treatments

The main treatments were a combination of residue management and soil tillage, namelly: (NT) no-till; (CP) chisel plow + 1 secondary disking; (CT) primary + 2 secondary disking; (CTb) CT wit crop residues burned; and (CTr) CT with crop residues removed from the field. They were established annually in plots 6 m wide and 30 m long, transversal to slope, before seeding of spring/summer cash crops. The chisel and the primary disking (in conventional tillage) plowed the soil down to respectively 25 and 15 cm depth. Winter cover crops were seeded in autumn using a direct drilling machine. A tractor with approximately 4.0 Mg and four-wheel drive was used to perform the primary tillage operations (i.e. primary disking and chisel plow) and a tractor with approximately 2.9 Mg and two–wheel drive was used to perform the secondary tillage operations (i.e. secondary disking) and seeding. Only soybean and triticale were harvested with a combine harvester with mass of about 10 Mg.

Nutrient sources treatments consisted of: (C) control without nutrients application; (MF) mineral fertilizers according to official recommendation for each crop (COMISSÃO DE FERTILIDADE DO SOLO – RS/SC, 1995); (PL) 5 Mg ha^{-1} y^{-1} of wet-matter of poultry litter; (CM) 60 m^3 ha^{-1} y^{-1} of slurry cattle manure; and (SM) 40 m^3 ha^{-1} y^{-1} of slurry swine manure. Nutrient sources were applied just before the summer crops seeding, in plots 6 m wide and 30 m long transversal to soil tillage systems (slope direction), before the secondary tillage. The amount of N, P_2O_5, and K_2O applied through different sources in nine years (cumulative) and in the tenth year of the experiment are showed in Table 5.2.

The experimental design consists of a factorial 5 x 5, with 25 treatment combinations and three replications applied in randomized subdivided blocks, as shown in Appendix A.

5.4.2 Chemical analysis

Chemical analysis was performed in disturbed samples collected at the end of ninth year of the experiment, at 0-5, 5-10, 10-20 and 20-40 cm layers. Soil for chemical analysis was sampled at four positions in each plot, mixed, oven dried at 60º C during 48 hours, ground with an electronic device and stored in paper boxes. The chemical analysis was performed at Laboratory for Soil Analysis of the Research Centre for Familiar Agriculture (Chapecó, SC), using methodology described in Tedesco et al. (1985).

Table 5.2 – Nutrient applied through different sources in nine years (cumulative) and in the tenth year of the experiment.

Nutrient source	Nutrient		
	N	P_2O_5	K_2O
9 years (cumulative)	-------------------------	kg ha^{-1}	-------------------------
Poultry litter	1106	847	882
Cattle manure	732	531	1019
Swine manure	1000	1507	526
Mineral fertilizer	675	450	690
10th year			
Poultry litter	29	34	15
Cattle manure	43	23	44
Swine manure	118	116	40
Mineral fertilizer	140	70	100

5.4.3 Corn leaf area index and height

Leaf area index and height of one representative plant per plot was measured weekly, from the emergence to beginning of flowering (66 days after emergence), when determinations were suspended because of a hail event which damaged the leaves. Corn height corresponds to the distance from the soil surface to position where the last two leaves cross over each other. Leaf area index (*LAI*, m^2 m^{-2}) was calculated from the length and width of photosintetically active leaves, using the following equation:

$$LAI = \left[\sum_{1=1}^{n} (Li * Wi * 0.75) * P \right] \tag{5.1}$$

Where ***L*** denotes the leaf length (m), ***W*** the leaf wide (m), ***P*** the corn population (plants m^{-2}), ***i*** the number of leaves, *n* the number of photosintetically active leaves, and *0.75* the corn leaf shape factor (Zhang and Brandle, 1997).

5.4.4 Corn root length and distribution

Material for this determination was sampled at corn flowering, approximately 80 days after seeding, using a riverside auger with 75 mm diameter, at 10 cm from a representative plant in each plot, at layers of 0-10, 10-20, 20-30, and 30-40 cm. Samples were placed in plastic pots with lid, transported to laboratory, and dispersed during 24 to 48 hours with a 0.20 N NaOH solution. After dispersion, samples were placed on a screen with 0.5 mm opening sieve and washed until total separation of roots from the soil. This procedure was performed in steps, removing roots previously separated by fluctuation from soil mass, in order to avoid additional root damage. Roots from each plot and depth were stored in plastic pots immersed in water, inside a refrigerator at 2ºC. Further removal of debris was done and root samples were finally stored immersed in a solution with 50% ethanol in the same refrigerator.

For scanning, roots were sprayed on a glass recipient with 17.5 x 29.5 cm surrounded by border of 1.0 cm high, with a shallow water layer, and scanned in color pictures using resolution of 600 dpi (dots per inch = 23.6 pixels mm^{-1}). Each sample was divided in as much subsamples as necessary to allow for good root distribution. Since this procedure did not resulted in good enough contrast to use directly in calculation of length and width using Rootedge software (Kaspar & Ewing, 1997), a previous procedure was performed using SPRING image processing software (Câmara et al, 1996) to highlight roots from the bottom. Total root length for each plot and depth corresponds to the sum of all subsamples.

5.4.5 Crop production

Canopy of winter cover crops was sampled before tillage operations in 0.5 m^2 area in each plot, oven-dried at 60ºC until constant dry-mass, weighted and dry-mass calculated in basis of kg ha^{-1}.

Corn production was measured in 16.8 m^2 harvested area (6 rows with 4 m length and 0.7 m interrow) in each plot and yield was calculated on basis of kg ha^{-1} of grains with 13% moisture.

5.3.6 Statistical analysis

Statistical analysis was performed using the Statistical Analysis System software (SAS, 1989). ANOVA test was determined for quantifying variances among soil management, nutrient source and depths (roots). Means differences were compared using the Tukey test ($P < 0.05$).

5.5 Results and discussion

5.5.1 Cumulative effect on soil fertility

Soil management and nutrient sources showed cumulative effect on basic soil fertility properties (Table 5.3). Lower values of soil pH, organic matter (OM), available P (P), and exchangeable K (K) were found in CTr treatment, because residues from the cash and cover crops were removed from the field, resulting in greater nutrients exportation. In average terms, all tillage treatments showed P and K values classified respectively as medium and high for this soil. Intermediates values found in NT treatment could be related to nutrient sources applications on the surface, without incorporation, resulting in loss of nutrients transported by runoff, especially when high intensity rainfall occurs a few days after manure application (Basso, 2003). Partial incorporation of nutrient sources in tilled treatments resulted in higher levels of available P and exchangeable K than in NT treatment from the top to deeper layers (Figure 5.1), showing that cumulative effect of nine years of nutrients application and residual effect of the last application were more important than natural trend of surface nutrient accumulation in NT system. It might be possible because tilled treatments had negligible erosion (visual observation), due to low slope at experiment place as well as the fact that tillage operations and seeding has been performed transversal to slope direction.

Greater variability in fertility parameters after nine years was found among nutrient sources, which is due to different amounts applied (Table 5.2) and exported among them during this period. As expected, lower values of OM, P and K were found in control, because no external input was made in this treatment. Greater pH in poultry litter might be due to the presence of calcium oxide mixed with this material, in order to allow reutilization and to avoid poultry diseases. Differences in P and K values are related to total amount applied, lost, and exported during time of experiment performing. This balance resulted in higher available P in poultry litter and swine manure and higher exchangeable K in mineral fertilizer treatment. Low exchangeable K in swine manure treatment is related to low total amount applied (low K content in swine manure) and high exportation through straw and grain.

Table 5.3 - Organic matter, pH, available P and exchangeable K at the end of the ninth year of applying five soil tillage systems and five nutrient sources.

Soil tillage	Nutrient source					
	C	PL	CM	SM	MF	Average
			Organic matter (g kg^{-1})			
NT	34	36	36	36	36	36 AB
CP	34	36	37	36	36	36 AB
CT	35	39	37	37	38	37 A
CTb	35	37	36	35	36	36 AB
CTr	35	36	35	34	35	35 B
Average	35 b	37 a	36 ab	36 ab	37 a	
			pH (1:1 soil:water)			
NT	5.1	5.2	5.3	5.2	5.1	5.2 AB
CP	5.2	5.4	5.3	5.4	5.0	5.3 A
CT	5.1	5.4	5.2	5.0	5.0	5.1 AB
CTb	5.1	5.3	5.0	4.9	5.0	5.1 AB
CTr	5.0	5.2	5.1	4.9	4.9	5.0 B
Average	5.1 bc	5.3 a	5.2 ab	5.1 bc	5.0 c	
			Available P (mg dm^{-3})			
NT	3.5	9.5	4.0	6.9	4.7	5.7 AB
CP	3.6	9.4	3.8	7.9	5.3	6.0 AB
CT	3.4	9.5	5.0	9.8	6.2	6.8 A
CTb	4.7	7.6	4.3	7.2	5.6	5.9 AB
CTr	3.3	7.0	4.1	6.8	3.9	5.0 B
Average	3.7 c	8.6 a	4.2 bc	7.7 a	5.2 b	
			Exchangeable K (mg dm^{-3})			
NT	66	115	147	57	158	109 BC
CP	82	154	194	96	228	151 A
CT	86	159	133	90	166	127 AB
CTb	108	149	146	94	178	135 AB
CTr	63	91	109	59	98	84 C
Average	81 c	134 b	146 ab	79 c	165 a	

NT = no-till; CP = chisel plow; CT = conventional tillage; CTb = CT with crop residues burned; CTr = CT with crop residues removed from the field; C = control; PL = poultry litter; CM = cattle manure; SM = swine manure; and MF = mineral fertilizer.
Means followed by the same small letters at a given row and capital letter at a given column are not statistically different (Tukey, $P < 0.05$).

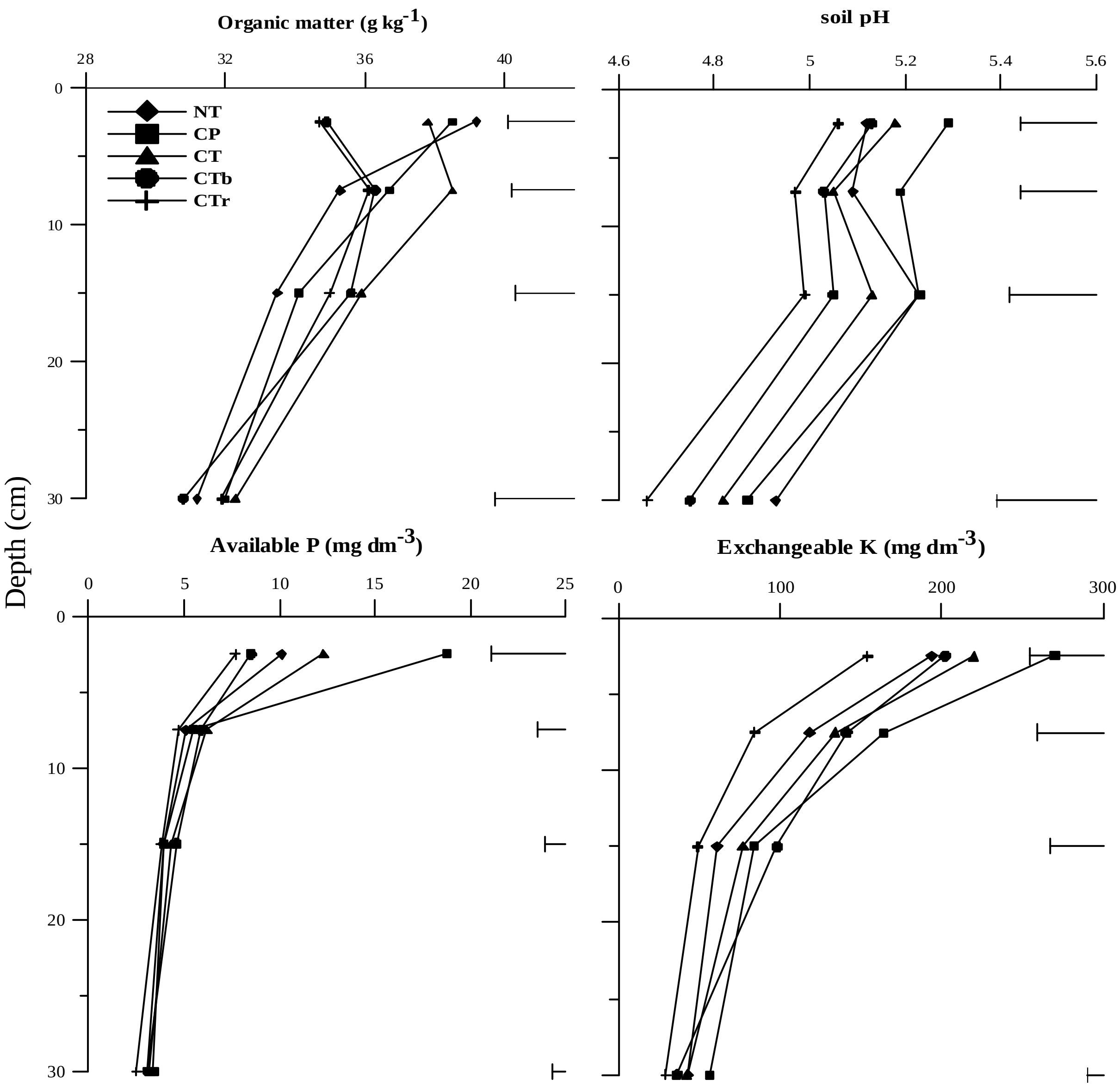

Figure 5.1 - Organic matter, soil pH, available P and exchangeable K at the end of ninth year of applying five soil tillage systems (averaged across nutrient sources). NT = no-till; CP = chisel plow; CT = conventional tillage; CTb = CT with crop residues burned; CTr = CT with crop residues removed from the field; horizontal bar at right position means least significant differences among treatments at each depth (Tukey, P<0.05).

5.5.2 Corn growth

Corn growth was affected both by soil management and nutrient sources treatment, but the last had higher effect on corn leaf area index and height until the beginning of flowering (Figure 5.2). Soil management treatments can be divided in two groups in terms of corn growth: (a) treatments where crop residues are kept on the field (NT, CP and CT), with higher growth; and (b) treatments with others destinations to crop residues (burned = CTb and removed = CTr), with lower growth. These differences could be explained mainly by the nitrogen supply to the corn from residue decomposition of winter cover crops and by the cumulative effect of burning and removing crop residues on soil chemical and physical properties, since soil moisture was high and similar among treatments in this period (Chapter 4).

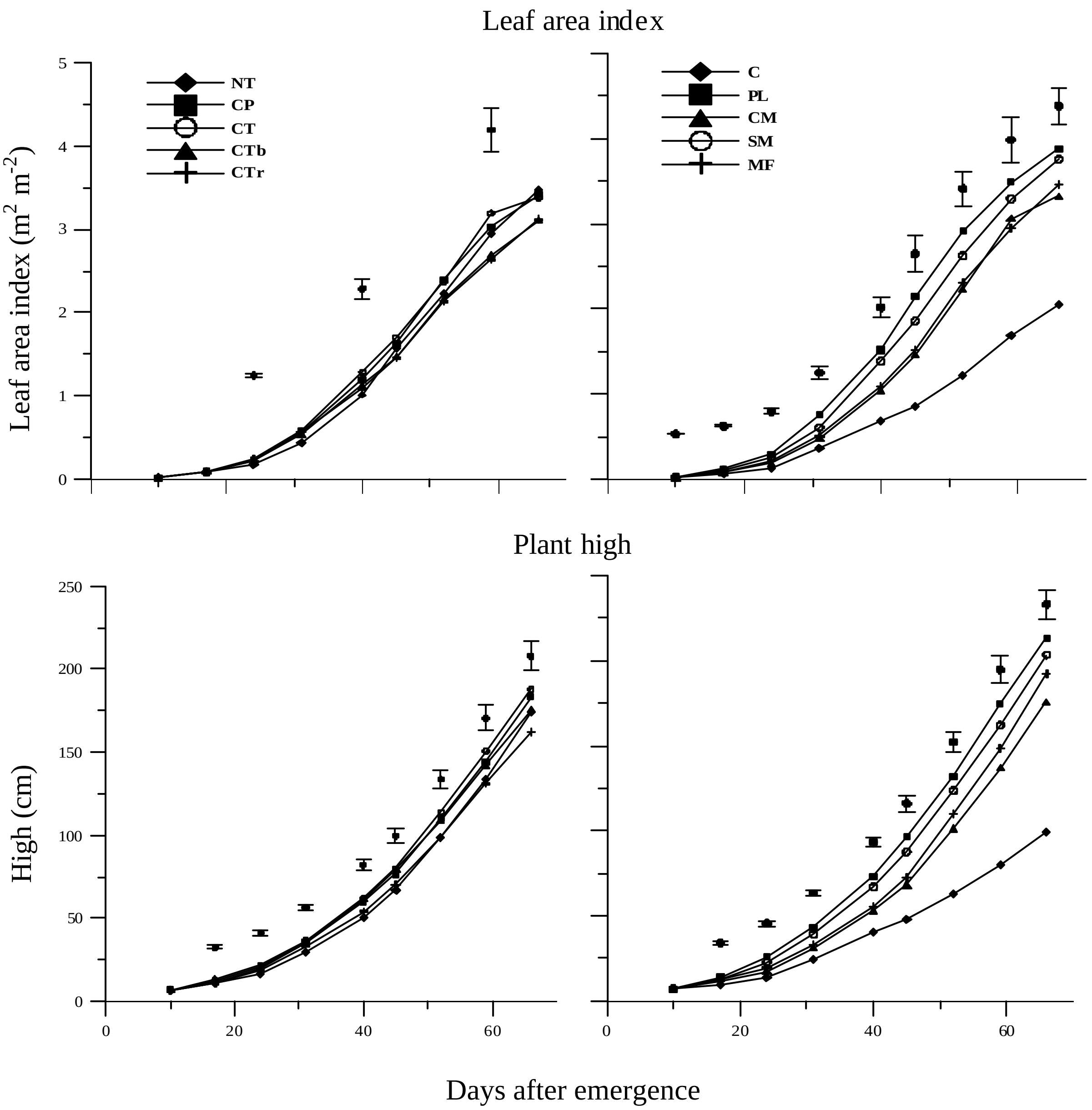

Figure 5.2 - Corn leaf area index and height in early corn growing period in five tillage systems (left, averaged across nutrient sources) and five nutrient sources (right, averaged across tillage systems). (NT = no-till; CP = chisel plow; CT = conventional tillage; CTb = CT with crop residues burned; CTr = CT with crop residues removed from the field; C = control; PL = poultry litter; CM = cattle manure; SM = swine manure; and MF = mineral fertilizer); vertical bars mean least significant differences among treatments at each time (Tukey, $P<0.05$).

The greater effect of nutrient sources on corn growth probably is due to higher cumulative effect on soil fertility and immediate effect of different amount of applying nutrients at seeding time (Table 5.2). As expected, lower corn growth was found in control treatment and is related to lower fertility and no nutrient application at seeding. Higher corn growth in poultry litter and swine manure treatments is related to higher cumulative soil fertility associated with immediate effect of nutrient application.

Root growth was affected by soil tillage at upper (0-10 cm) and lower layer (30-40 cm), and no significant effect was found at intermediate ones or when root density were pulled together for whole measured layers (Table 5.4). Greater root density was observed in NT and CP treatment at 0-10 cm depth layer and in CP at 30-40 cm depth layer. This treatment showed better root distribution at the depths sampled, resulting from lower penetration resistance in the upper layers on untrafficked interrow position (Chapter 3) where roots were sampled. On the other hand, greater root density at upper layer in NT treatment could be related to greater water retention found at this layer in dryer periods.

Differences in root growth among nutrient sources were observed in deeper layers (20-30 and 30-40 cm), where greater root density was observed in mineral fertilizer and lower in control treatments, and is related to nutrient availability at these depths, mainly exchangeable K.

5.5.3 Crop production

Results of dry-mass of the winter cover crops and corn grain production are shown respectively in Tables 5.5 and 5.6. There were no interactions between soil tillage and nutrient sources treatments, and means were compared for soil tillage within nutrient sources and for nutrient sources within soil tillage.

There was no statistically significant differences in dry-mass production of winter cover crops among tillage treatments, probably because the level of the main nutrients, in average terms, were similar among them (except for K in CTr), and cover crops used are not highly responsive to low variation in nutrient availability. Among the nutrient sources, greater dry-mass production was found for treatments which resulted in better cumulative soil fertility properties, and differences were statistically different among them.

Table 5.4 - Root density (cm cm^{-3}) at corn flowering measured at four depths in the tenth year of applying five soil tillage systems and five nutrient sources.

Soil tillage	Nutrient source					
	C	PL	CM	SM	MF	Average
			0 – 10 cm			
NT	4.38	4.30	3.59	3.08	3.81	3.83 A
CP	4.64	3.17	3.47	3.44	2.52	3.45 AB
CT	3.41	2.32	2.30	2.35	3.25	2.72 BC
CTb	2.42	2.39	2.44	2.64	1.82	2.34 C
CTr	2.43	2.61	3.04	2.50	2.90	2.70 BC
Average	3.46 a	2.96 a	2.97 a	2.80 a	2.86 a	
			10 – 20 cm			
NT	2.80	1.82	1.71	1.73	2.07	2.02 A
CP	1.90	2.74	2.57	2.54	2.28	2.41 A
CT	3.26	2.32	3.18	2.37	2.68	2.76 A
CTb	2.91	2.78	2.54	2.74	2.08	2.61 A
CTr	2.49	2.72	3.88	2.45	2.37	2.78 A
Average	2.67 a	2.48 a	2.77 a	2.37 a	2.30 a	
			20 – 30 cm			
NT	2.15	2.30	2.11	2.59	2.72	2.37 A
CP	2.62	2.31	2.32	2.60	2.74	2.52 A
CT	2.13	2.38	2.50	2.06	2.69	2.35 A
CTb	1.72	2.13	2.69	1.97	2.26	2.15 A
CTr	1.44	3.20	2.41	1.96	3.27	2.46 A
Average	2.01 b	2.46 ab	2.40 ab	2.24 ab	2.73 a	
			30 – 40 cm			
NT	1.23	1.41	1.24	1.72	1.65	1.45 AB
CP	1.88	1.99	2.01	2.07	2.15	2.02 A
CT	1.02	2.04	1.95	1.38	2.20	1.72 AB
CTb	1.12	1.22	1.38	1.75	2.13	1.52 AB
CTr	0.70	1.96	1.41	1.58	1.25	1.38 B
Average	1.19 b	1.72 ab	1.60 ab	1.70 ab	1.87 a	
			0 – 40 cm			
NT	2.64	2.46	2.16	2.28	2.56	2.42 A
CP	2.76	2.55	2.59	2.66	2.42	2.60 A
CT	2.45	2.26	2.48	2.04	2.70	2.39 A
CTb	2.04	2.13	2.26	2.27	2.07	2.16 A
CTr	1.76	2.62	2.69	2.13	2.45	2.33 A
Average	2.33 a	2.41 a	2.44 a	2.28 a	2.44 a	

NT = no-till; CP = chisel plow; CT = conventional tillage; CTb = CT with crop residues burned; CTr = CT with crop residues removed from the field; C = control; PL = poultry litter; CM = cattle manure; SM = swine manure; and MF = mineral fertilizer.

Means followed by the same small letters at a given row and capital letter at a given column are not statistically different (Tukey, $P < 0.05$).

Table 5.5 - Dry-mass production of winter cover crops (common vetch + black oat) in the tenth year of applying five soil tillage systems and five nutrient sources.

Soil tillage	Nutrient source					
	C	PL	CM	SM	MF	Average
	------------------------ kg ha^{-1} ------------------------					
NT	2287	3473	3047	3913	2807	3105 A
CP	3107	4673	2900	4333	3087	3620 A
CT	2127	3293	3727	3287	2933	3105 A
CTb	2353	3480	2700	4007	2987	3073 A
CTr	1600	4067	2800	3547	2747	2952 A
Average	2295 c	3797 a	3035 b	3817 a	2912 bc	

NT = no-till; CP = chisel plow; CT = conventional tillage; CTb = CT with crop residues burned; CTr = CT with crop residues removed from the field; C = control; PL = poultry litter; CM = cattle manure; SM = swine manure; and MF = mineral fertilizer.

Means followed by the same small letters at a given row and capital letter at a given column are not statistically different (Tukey, P< 0.05).

Corn grain production was higher in tillage treatments where plant residues were kept in the field (NT, CP and CT), without significant differences among them. When residues were burned (CTb) or removed from the field (CTr), lower grain yield were found, and differences were greater in control treatment, without nutrient application (Table 5.6). Higher grain production in NT probably is related to greater water availability found in this treatment in the dryer period (from flowering to physiological maturation), since soil fertility was similar to CP and CT, except in lower exchangeable K content. Lower water retention at the upper layer (0-23 cm) for CP treatment was probably compensated by greater root growth in deeper layer, where water content was similar or even greater than in NT and CT treatments (Chapter 4).

Table 5.6 - Corn grain yield in the tenth year of applying five soil tillage systems and five nutrient sources.

Soil tillage	Nutrient source					
	C	PL	CM	SM	MF	Average
	------------------------ kg ha^{-1} ------------------------					
NT	1719	5471	4624	4983	4412	4242 A
CP	1893	5064	4112	4745	4191	4001 AB
CT	1575	5023	3943	4837	4218	3920 AB
CTb	980	4564	3849	4651	3955	3600 BC
CTr	693	4691	3377	3867	3306	3187 C
Average	1372 c	4963 a	3981 b	4617 a	4016 b	

NT = no-till; CP = chisel plow; CT = conventional tillage; CTb = CT with crop residues burned; CTr = CT with crop residues removed from the field; C = control; PL = poultry litter; CM = cattle manure; SM = swine manure; and MF = mineral fertilizer

Means followed by the same small letters at a given row and capital letter at a given column are not statistically different (Tukey, P< 0.05).

The cumulative effect on soil fertility of applying nutrients from different sources reflected in corn grain production. Greater pH, available P and especially exchangeable K found for poultry litter seems to be determinant in corn grain production, since lower amount of N, P and K were applied at seeding time in this year, compared to other sources. The same trend was observed between cattle manure and mineral fertilizer treatments, which showed similar grain production even with much higher P and K application through mineral fertilizers treatment.

5.6 Conclusions

Partial incorporation of nutrient sources in tilled treatments resulted in concentration of nutrients in the upper layers and in higher levels of available P and exchangeable K than in NT system.

Crop residues removal from the field resulted in reduction in basic soil fertility properties and, as a consequence, in crop production.

Cumulative effect of applying poultry litter and swine manure resulted in greater soil fertility and crop production, both reflecting residual and immediate effects.

The greater crop production observed in NT system is closer related to water retention during dryer period, than basic soil fertility.

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APÊNDICE

Appendix A - Croquis of the experiment.

Block 1 **(Up hill)**

	PL	C	MF	CM	SM
CTb	1	2	3	4	5
CTr	6	7	8	9	10
CT	11	12	13	14	15
NT	16	17	18	19	20
CP	21	22	23	24	25

Block 2 **(middle hill)**

	MF	SM	CM	PL	C
CP	26	27	28	29	30
CTr	31	32	33	34	35
CTb	36	37	38	39	40
CT	41	42	43	44	45
NT	46	47	48	49	50

Block 3 **(down hill)**

	C	CM	SM	MF	PL
NT	51	52	53	54	55
CP	56	57	58	59	60
CT	61	62	63	64	65
CTr	66	67	68	69	70
CTb	71	72	73	74	75

NT = no-till; CP = chisel plow; CT = conventional tillage; CTb = CT with crop residues burned; CTr = CT with crop residues removed; C = nutrient source control; MF = mineral fertilizer; PL = poultry litter; CM = cattle liquid manure; and SM = swine liquid manure.