UNIVERSIDADE FEDERAL DE LAVRAS

PIERO IORI

EFEITO DO TEMPO DE IMPLANTAÇÃO DE LAVOURA CAFEEIRA E DA DECLIVIDADE DO TERRENO EM PROPRIEDADES FÍSICO-MECÂNICAS DE UM LATOSSOLO VERMELHO-AMARELO

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Tese apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-Graduação em Ciência do Solo, área de concentração em Recursos Ambientais e Uso da Terra, para a obtenção do título de Doutor.

Orientador

PhD Moacir de Souza Dias Junior

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Ficha Catalográfica Elaborada pela Divisão de Processos Técnicos da Biblioteca da UFLA

Iori, Piero.
Efeito do tempo de implantação de lavoura cafeeira e da declividade do terreno em propriedades físico-mecânicas de um Latossolo Vermelho-Amarelo / Piero Iori. – Lavras : UFLA, 2012.
96 p. : il.

Tese (doutorado) – Universidade Federal de Lavras, 2012.
Orientador: Moacir de Souza Dias Junior.
Bibliografia.

1. *Coffea arabica* L. 2. Solo. 3. Pressão de pré-consolidação. 4. Compactação. 5. Tráfego agrícola. 6. Capacidade de suporte de carga. 7. Física do solo. I. Universidade Federal de Lavras. II. Título.

CDD – 631.43

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APROVADA em 23 de novembro de 2012.

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LAVRAS – MG
2012

A minha esposa, Cecilia Armesto, por sempre estar ao meu lado.

DEDICO

Agradecimentos

À Universidade Federal de Lavras (UFLA) e ao Departamento de Ciência do Solo (DCS), pela oportunidade de realização do doutorado.

À Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (Capes) pela concessão da bolsa de estudos.

À Empresa de Pesquisa Agropecuária de Minas Gerais (EPAMIG), pelo apoio e disponibilização de funcionários, fundamentais para a conclusão deste trabalho.

Ao Consórcio Brasileiro de Pesquisa e Desenvolvimento do Café CBP&D/Café, pelo suporte financeiro para o desenvolvimento desta pesquisa.

Ao professor Moacir de Souza Dias Junior, pela oportunidade de trabalhar ao seu lado e pela amizade, ensinamentos e orientação, indispensável na conclusão deste trabalho.

Ao pesquisador Paulo Tácito Gontijo Guimarães, pela coorientação e parceria, que muito contribuiu para o andamento e a finalização deste trabalho.

Aos professores Geraldo Cesar de Oliveira, Mozart Martins Ferreira e Wellington Willian Rocha e ao pesquisador Elifas Nunes Alcântara, por participar da banca examinadora e pelas críticas e sugestões apresentadas, fundamentais para a conclusão deste trabalho.

Aos professores Reginaldo Barboza da Silva e Nilton Curi, pelas ótimas conversas e conselhos transmitidos.

A todos os demais professores do DCS/UFLA, pelo conhecimento transmitido e conversas agradáveis.

A minha esposa, companheira e parceira, Cecilia, pelo apoio, dedicação, conselhos, ensinamentos, carinho, motivação e, principalmente, me fazer feliz e por estar ao meu lado, sempre.

Aos meus pais, João Ferreira da Silva e Auzana Rodrigues Villar da Silva (*in memoriam*), aos meus irmãos João Guilherme e Janaina, aos meus tios Doralice Villar e Euclides Siguero, ao meu primo Julian Villar Neto e a minha família por parte da Cecilia, Juan, Joana, Mariana e Bráulio, por todo auxílio.

Aos amigos, parceiros e funcionários do Laboratório de Física do Solo, Dulce e Doroteo, pela amizade e auxílio na realização das análises.

Aos amigos Áureo, Vanessa e Zélio, pela ajuda fornecida, o que foi fundamental para a realização e conclusão deste trabalho.

A todos os amigos de Departamento e de pós-graduação Dirce, Maria Alice, Pezão, Cezar, Bruno, Eduardo, Paulinha, Malu, Carla, Bruno, Adriana, Raphael, Paula e pessoal do futebol.

Aos meus grandes amigos Diego França e Everton Pires Soliman, pelas ótimas conversas desde a graduação.

Ao meu grande amigo Woody.

RESUMO

A cafeicultura brasileira é um importante gerador de divisas, e, como maior produtor mundial de café, o Brasil é responsável por um terço do total de café produzido no mundo. O desenvolvimento destacado deste setor no cenário mundial, muito se deve a alta tecnologia aplicada, principalmente mecanizada, que ocupa todas as fases de produção do café. Isto tem sido relatado como principal causador da degradação da estrutura dos solos agrícolas, que na maioria dos casos se apresenta na forma da compactação do solo. A declividade do terreno associada ao tempo de cultivo de lavouras cafeeiras tem tornado este quadro ainda mais crítico, devido às operações mecanizadas serem realizados em terrenos com diferentes declividades, alterando o seu centro de gravidade e aumentando o impacto no solo sob um determinado eixo e/ou rodado do trator. As hipóteses deste trabalho foram: 1) as alterações nos atributos físico-mecânicos do solo, em áreas cultivadas com cafeeiro são função do declive e do tempo de implantação do cafezal e 2) os impactos das operações mecanizadas sobre a estrutura do solo são diferentes nas linhas de tráfego (de cima ou de baixo), bem como, na entrelinha do cafeeiro. Este trabalho foi organizado em duas partes e o objetivo foi analisar em áreas cafeeiras com diferentes tempos de cultivo, o efeito do tráfego de máquinas sobre a estrutura de um Latossolo Vermelho-Amarelo em terrenos com diferentes declividades. A primeira parte contém uma introdução e um referencial teórico sobre a cultura do café. Na segunda parte são apresentados três artigos científicos. Para o artigo 1, o objetivo foi avaliar o efeito do tráfego agrícola sobre as propriedades físicas de um Latossolo Vermelho-Amarelo cultivado com cafeeiro em diferentes tempos de cultivo e em diferentes declividades do terreno. O objetivo do artigo 2, foi comparar modelos de capacidade de suporte de carga obtidos com umidade controlada em laboratório com os obtidos com umidade natural de campo ao longo de um ano. Por fim, o artigo 3 teve como objetivo avaliar o comportamento da pressão de pré-consolidação no decorrer de um ano em um Latossolo Vermelho-Amarelo cultivado com cafeeiros de diferentes tempos de implantação em diversas declividades do terreno. Este estudo foi conduzido em plantações cafeeiras localizadas em Três Pontas, sul de Minas Gerais (24°26’ S; 47°49’ O’ e altitude de 905m). O clima da região é o Cwa, com temperatura média de 18°C e com precipitação média anual de 1.300 mm. O solo da área de estudo foi classificado como Latossolo Vermelho-Amarelo, com 510 g kg^{-1} de argila, 200 g kg^{-1} de areia e 290 g kg^{-1} de silte e densidade de partículas de 2,62 Mg m^{-3}. O trator utilizado na área de estudo foi um Massey Ferguson 265 com massa de aproximadamente 3.940 kg. Este estudo foi conduzido em plantações cafeeiras com 2, 7, 18 e 33 anos de implantação. Nestas plantações foram selecionados terrenos com 3, 9 e 15% de declividade. Foram coletadas amostras de solo indeformadas e deformadas na linha de tráfego de cima e de baixo e na entrelinha do cafeeiro, nas camadas de 0,0 a 0,03 m e 0,15 a 0,18 m. Para a elaboração do artigo 1 desta tese foi realizado as seguintes análises: granulometria, densidade do solo, porosidade total, macro e microporosidade, estabilidade de agregados e matéria orgânica do solo. No artigo 2, os ensaios de compressão uniaxial do solo e as estimativas da pressão de pré-consolidação em laboratório foram obtidas para duas condições, com umidade controlada em laboratório e com umidade natural, obtidas ao longo de um ano no campo. Após isso foram obtidos os modelos de capacidade de suporte de carga para as duas condições. Por fim, para verificar se os modelos de capacidade de suporte de carga obtidos com umidade controlada em laboratório podem representar os modelos de capacidade de suporte de carga obtidos com umidade natural, estes modelos foram comparados utilizando o teste de homogeneidade de dados. Para o artigo 3, os ensaios de compressão uniaxial do solo e as estimativas da pressão de pré-consolidação foram obtidas com umidade natural, ou seja, obtidas com umidade de campo ao longo de um ano. Este estudo mostrou que entre os fatores estudados, o tempo de implantação e de cultivo foi o fator que afetou a maioria das propriedades físicas do solo, já a declividade do terreno influenciou a matéria orgânica do solo, microporosidade e a estabilidade de agregados. A entrelinha apresentou os melhores resultados em termos de preservação da estrutura do solo e a linha de tráfego na parte de baixo do terreno apresentou melhores resultados do que a linha de tráfego na parte de cima do terreno. Além disso, verificou-se que 75% dos modelos de capacidade de suporte de carga do solo obtidos com umidade de campo foram semelhantes aos modelos obtidos com umidade controlada em laboratório. Portanto, os resultados sugerem que a análise da sustentabilidade da estrutura do solo pode ser feita por modelos de capacidade de suporte carga obtidos com amostras de solo obtidas com umidade natural (campo) ou com umidade controlada (laboratório). Por fim, a avaliação da pressão de pré-consolidação ao longo de um ano indicou que o tempo de cultivo e a declividade do terreno tiveram um efeito significativo sobre a alteração estrutural do solo, sendo as áreas com maior tempo de cultivo e as mais declivosas que apresentaram os maiores valores de pressão de pré-consolidação. A linha de tráfego de cima apresentou maior capacidade de suporte de carga do que a entrelinha e a linha de tráfego de baixo. O período de novembro a janeiro foi a época mais crítica para o tráfego agrícola, devido o Latossolo Vermelho-Amarelo apresentar baixa capacidade de suporte de carga e ser este o período crítico em termos de umidade no solo.

Palavras-Chave: Capacidade de suporte de carga do solo. *Coffea Arabica L.* Compactação do solo. Pressão de pré-consolidação. Tráfego agrícola.

ABSTRACT

The Brazilian coffee is an important generator of foreign exchange, and as world's largest producer of coffee, Brazil is responsible for 33% of the total coffee produced in the world. The outstanding development of this sector on the world stage, due to very high technology applied mainly mechanized, which occupies all phases of coffee production. This has been reported as a major cause of degradation of the structure of agricultural soils. The slope of the inter-row coffee plantations associated with the establishment time of coffee plantation can influence the location of the center of gravity of operating machine, thereby resulting in differentiated impact and effect on stress distribution in soil under a given machine axis and along the wheel track. The hypotheses of this study were: 1) the alterations in the physical-mechanical soil attributes in areas cultivated with coffee are a function of the slope and the establishment time of coffee and 2) the impacts of mechanized operations on soil structure are different in traffic lines (top or bottom) and inter-row of coffee plantation. This work was organized in two parts and the objective was to analyze in coffee areas with different establishment times, the effect of machinery traffic on the soil structure of a Red-Yellow Latosol on the coffee row with different slopes. The first part contains an introduction and a theoretical framework about the coffee culture. In the second part there are three articles. For article 1, the objective of this study was to analyze in coffee plantation with different establishment times, the effect of machine traffic on the soil physical properties in clayey Red-Yellow Latosol planted to coffee at different side slopes. The objective of article 2 was to compare the load bearing capacity models obtained with controlled moisture in laboratory and those obtained with natural field moistures determined a long one year. The objective of the article 3 was to describe the seasonal change of soil precompression stress behavior in coffee plantations in the sub-humid tropic zone of Brazil as affected by agriculture traffic associated to the time since the establishment the coffee plantation, the filed slope and in three sampling position in inter-row of the coffee plantation. This study was conducted in coffee plantations located in Três Pontas County, South of Minas Gerais State, Brazil (24°26’ S; 47°49’ W’ and altitude of 905m). The climate according to Koppen is Cwa, that is, altitude tropical, with an average annual temperature of about 18° C. The annual rainfall measured during the study was 1330 mm. The soil of the study area was classified as a clayey textured Red-Yellow Latosol (Oxisol) with 510 g kg^{-1} of clay, 200 g kg^{-1} of sand and 290 g kg^{-1} of silt, and particle density of 2.62 g cm^{-3}. All the equipment used in the coffee crop management was pulled by a Massey Ferguson 265 tractor, with a mass of about 3,940 kg. This study was conducted in coffee plantations with 2, 7, 18 and 33 years of establishment. In these coffee plantations were selected areas (coffee row) with side slope of 3, 9 and 15%.

The soil was sampled at three positions on the coffee row: bottom of traffic line, inter-row and top of traffic line at two layers: 0.00 m – 0.03 m (topsoil) and 0.15 m – 0.18 m (sub-surface). In the article 1, changes were investigated on the total porosity, macroporosity, microporosity, organic matter, bulk density and aggregate stability. In the article 2, the evaluation of soil structural sustainability follows four distinct steps: soil sampling in the field, uniaxial compression test of the samples in the laboratory, determination of precompression stress and estimation of the load bearing capacity models. Laboratory estimates of precompression stress were obtained from moisture controlled in laboratory and from natural moisture determined in a field a long one year. In this process, the soil samples were saturated by capillarity with distilled water in laboratory, and after 48 hours, the samples were air dried to obtain the different moisture contents. Then, the precompression stress was determined for this both conditions. To verify if the load bearing capacity models obtained with controlled moisture in laboratory may represent the load bearing models obtained with natural field moisture, these models were compared using the homogeneity test procedure. For article 3, the uniaxial compression tests were realized with soil samples at the field moisture content a long one year. This study showed that among the factors, the establishment time (coffee age) was the factor that affected most of the soil properties. Field slope influenced reasonably the soil physical properties, particularly organic matter, microporosity and aggregate stability. The samples from the inter-row were the best in terms of the preservation of soil structure than samples from traffic lines (bottom and top traffic line) and samples from the bottom traffic line showed better results in terms of soil structure preservation than those from the top traffic line. It was observed that 75% of field models analyzed were similar to the laboratory models. Thus, due to the similarity on the load-bearing capacity models obtained using natural (field) or controlled (laboratory) moisture contents, the assessment of the soil structure sustainability can be done using both methods. Finally, this study also showed that the time since the establishment of a coffee farm and the slope steepness had significant effect on soil disturbance in mechanized operation, with areas that the coffee plants with longer establishment time and with more terrain lateral inclination had higher precompression stress. Top traffic line presented higher load-bearing capacity than inter-row and bottom traffic line. The period from November to January is the period that the soil is more susceptible to compaction, because the Red-Yellow Latosol presented lower load-bearing capacity than the stress applied by tractor used in coffee management practices.

Keywords: Agricultural traffic. *Coffea Arabica L.* Soil load bearing capacity. Preconsolidation pressure. Soil compaction.

SUMÁRIO

PRIMEIRA PARTE

1 INTRODUÇÃO

A cafeicultura tem posição de destaque no Brasil e no cenário internacional, representando o quinto item na pauta de exportações do agronegócio, gerando US$ 8,7 bilhões para a economia do Brasil (MAPA, 2012). O agronegócio do café emprega direta e indiretamente, mundialmente, cerca de meio bilhão de pessoas, ou seja, 8% da população mundial desde a sua produção até o seu consumo final. No Brasil, este é o setor do agronegócio brasileiro que mais emprega, gerando mais de 8 milhões de empregos diretos e indiretos no país (CAMPOS, 2005). Resultados e estimativas indicam que o ano de 2012 apresentará um crescimento de 16,1% quando comparado com a produção obtida na safra anterior (CONAB, 2012).

Indiscutivelmente o setor cafeeiro apresenta elevada importância nacional e internacional, e apresenta resultados expressivos em termos de produção devido à intensa tecnificação do setor, principalmente na parte de máquinas agrícolas. Se por um lado a mecanização agrícola traz resultados significativos em termos financeiros, por outro, pode acarretar problemas sérios de degradação da estrutura do solo. Operações mecanizadas realizadas de maneira incorreta ou mesmo em situações adversas, ao longo dos anos, podem acentuar a degradação física dos solos.

O solo é o patrimônio mais importante para qualquer nação do mundo, e como tal tem que ser utilizado de maneira sustentável, respeitando seus limites. O uso inadequado do tráfego agrícola pode acelerar a degradação da estrutura do solo, podendo levar a uma redução significativa da produtividade da cultura do cafeeiro (MIRANDA et al., 2003).

O tráfego agrícola em áreas cultivadas com cafeeiros com condições inadequadas tem-se tornado preocupante, e diversos autores já relataram problemas em decorrência da compactação do solo (MIRANDA et al., 2003; SILVA et al., 2006; ARAUJO-JUNIOR; DIAS JUNIOR; GUIMARÃES, 2008; SANTOS et al., 2009; PAIS et al., 2011; ARAUJO-JUNIOR et al., 2011; MARTINS et al., 2012). O tráfego agrícola em condições adversas de umidade do solo pode acarretar em significativas alterações no comportamento estrutural do solo. Dias Junior (1994) destaca que para uma mesma condição, a umidade é o fator que governa a quantidade de deformação que poderá ocorrer no solo.

Além da umidade do solo, outros fatores podem acentuar as modificações da estrutura no solo, destacando os diferentes sistemas de manejo (MIRANDA et al., 2003), operações mecanizadas e intensidade de tráfego (SILVA et al., 2006), manejo da planta daninha na entrelinha do cafeeiro (ARAUJO-JUNIOR; DIAS JUNIOR; GUIMARÃES, 2008; SANTOS et al., 2009; PAIS et al., 2011 e ARAUJO-JUNIOR et al., 2011) e tempo de estabelecimento da cultura (MARTINS et al., 2012).

Uma nova abordagem a ser investigada em solos cultivados com cafeeiros, é o efeito da declividade do terreno, pois o manejo do maquinário agrícola em áreas declivosas cultivadas com cafeeiros tem influenciado a estrutura do solo (MARTINS et al., 2012). Jamshidi et al. (2008) citam que em terrenos declivosos, a distribuição de carga é desigual entre os pneus, o que resulta em um maior pico de pressão dinâmica exercida sobre o solo. Najafi; Solgi; Sadeghi (2009) também verificaram o impacto da intensidade de tráfego no solo devido a sua declividade, e observaram que durante a patinagem em um terreno íngreme, a carga é aplicada de forma desigual sobre os eixos aumentando o revolvimento e impacto no solo sob este eixo e/ou rodado.

Estudos recentes realizados por Martins et al. (2012) sugerem que em futuros estudos de compactação do solo, a declividade deveria ser abordada e que se deveria considerar separadamente as linhas de tráfego localizados na parte superior e inferior do terreno, para melhor quantificar o efeito da compactação sobre a estrutura do solo.

Deste modo, as hipóteses deste trabalho foram: 1) as alterações nos atributos físico-mecânicos do solo, em áreas cultivadas com cafeeiros são função do declive do terreno e do tempo de implantação dos cafeeiros e 2) os impactos das operações mecanizadas sobre a estrutura do solo são diferentes nas linhas de tráfego (parte superior e inferior do terreno), bem como, na entrelinha do cafeeiro. Para isso, este trabalho foi conduzido com o objetivo de analisar em áreas cafeeiras com diferente tempo de cultivo, o efeito do tráfego de máquinas sobre a estrutura de Latossolo Vermelho-Amarelo localizados em terrenos com diferentes declividades.

Os objetivos específicos deste estudo foram:

a) avaliar o efeito do tráfego do maquinário agrícola sobre as propriedades físicas de um Latossolo Vermelho-Amarelo cultivado com cafeeiro em diferentes tempos de cultivo e localizado em terrenos com diferentes declividades.

b) comparar modelos de capacidade de suporte de carga do solo do solo obtidos com umidade controlada em laboratório com os obtidos com umidade natural de campo obtido ao longo de um ano.

c) avaliar o comportamento da pressão de pré-consolidação no decorrer de um ano num Latossolo Vermelho-Amarelo cultivado com cafeeiros em diferentes tempos de implantação e em diversas declividades do terreno.

2 REFERENCIAL TEÓRICO

2.1 Cultura do cafeeiro

A cultura do café chegou ao norte do Brasil, mais precisamente em Belém, em 1727, trazido da Guiana Francesa pelo Sargento-Mor Francisco de Mello Palheta a pedido do governador do Maranhão e Grão Pará. Já naquela época a cultura do café possuía grande valor comercial. Devido às nossas condições climáticas, o esta cultura se espalhou rapidamente, com a produção voltada para o mercado doméstico. Em sua trajetória pelo Brasil a cultura do café passou pelo Maranhão, Bahia, Rio de Janeiro, São Paulo, Paraná e Minas Gerais. Num espaço de tempo relativamente curto, a produção do café passou de uma posição relativamente secundária para a de produto-base da economia brasileira (ABIC, 2010).

Desde sua chegada ao país, a cultura cafeeira foi o maior gerador de riquezas e seu produto o mais importante da história nacional (CAMPOS, 2005). As primeiras exportações expressivas ocorreram em 1802. Entre 1925 e 1929, o café chegou a contribuir isoladamente com 70% do valor das exportações brasileiras. A partir da década de 70, a produção ganhou um grande impulso com a conquista das regiões do cerrado (MAPA, 2008).

O Brasil é o maior produtor mundial de café, à frente do Vietnã (20 milhões de sacas), da Indonésia (8,25 milhões de sacas), Colômbia (7,8 milhões de sacas) e Etiópia (6,5 milhões de sacas) (OIC, 2012). Os dados de 2011 mostram que a safra do grão alcançou 43,48 milhões de sacas, sendo responsável por um terço do total de café produzido no mundo e este setor representou o quinto item das exportações brasileiras, com 9,2% de participação nas exportações do agronegócio, gerando US$ 8,7 bilhões para a economia do

Brasil. Os principais países importadores do café brasileiro são Estados Unidos, Alemanha, Itália e Japão (MAPA, 2012).

A terceira estimativa de produção de café (arábica e conilon) para a safra 2012 indica que o país deverá colher 50,48 milhões de sacas de 60 quilos do produto beneficiado. O resultado representa um crescimento de 16,1% quando comparado com a produção obtida na safra de 2011, que foi de 43,48 milhões de sacas. Esse crescimento se deve principalmente ao ano de alta bienalidade. Confirmando este resultado, esta será a maior safra já produzida no país, superando o volume de 48,48 milhões de sacas colhidas na safra 2002/03 (CONAB, 2012).

O agronegócio do café emprega direta e indiretamente, mundialmente, cerca de meio bilhão de pessoas, ou seja, 8% da população mundial, desde a sua produção até o seu consumo final. No Brasil, este setor do agronegócio é o que mais emprega, gerando mais de 8 milhões de empregos diretos e indiretos no país (CAMPOS, 2005). O Brasil é segundo maior consumidor de café do mundo e seu o consumo continua crescendo. No período compreendido entre Maio/2011 e Abril/2012, a ABIC registrou o consumo de 19,975 milhões de sacas, representando um acréscimo e 3,05% em relação ao período anterior correspondente (Maio/2010 a Abril/2011), que havia sido de 19,383 milhões de sacas (ABIC, 2012).

Minas Gerais é o maior produtor brasileiro e colheu em 2011, cerca de 22,2 milhões de sacas de café, o que representou 51% do total da safra nacional (CONAB, 2012). A região Sul e Centro-Oeste de Minas Gerais respondeu por 50% da produção do Estado em 2011 (MAPA, 2012). Três Pontas é um município localizado no sul do estado de Minas Gerais, em que a principal atividade da região é o cultivo do café. A economia deste município é mista, onde a pequena e média indústria convivem com a agricultura, que tem como base a cafeicultura. O plantio é diversificado, mas os cafezais ocupam a maior parte da área cultivada, elevando Três Pontas como a "Capital Mundial do Café". Existem no município mais de 70 milhões de cafeeiros plantados, numa área de 24 mil hectares, sendo o maior produtor nacional (PREFEITURA, 2010).

2.2 Compactação e comportamento compressivo do solo

A compactação do solo é considerada como a principal causadora da degradação dos solos agrícolas (CANILLAS; SALOKHE, 2002) e é um processo pelo qual ocorre a expulsão de ar e consequentemente a redução de volume do mesmo (DIAS JUNIOR; MIRANDA, 2000). De acordo com Hillel (2004), o problema da compactação do solo parece ter piorado nos dias atuais, juntamente com a crescente necessidade de utilização de máquinas agricolas maiores e mais pesadas e a tendência de repetido tráfego, devido a diversas situações, como semeadura, adubação, controle de pragas, colheita, entre outras. Richart et. (2005) também destaca que os solos agrícolas vêm sofrendo grandes perturbações, sendo a compactação apontada como a principal causa destas mudanças em virtude do tráfego de tratores e máquinas agrícolas em condições inadequadas de manejo.

A compactação no solo pode resultar em alterações de diversas propriedades do solo. Dentre elas, pode-se destacar a redução da porosidade do solo, principalmente sua fração ocupada por ar, reduzindo a aeração do solo, diminuição do tamanho e continuidade dos poros, redução da infiltração de água com aumento da densidade do solo, resistência mecânica do solo e escoamento superficial (DIAS JUNIOR, 2000; SILVA et al., 2003a; SEVERIANO et al., 2008; SILVA et al., 2009; ARAUJO-JUNIOR et al., 2011; PIRES et al., 2012).

De acordo com GONTIJO et al. (2008), a carga excessiva aplicada ao solo devido as operações mecanizadas reduzem os macroporos devido ao colapso da estrutura do solo, reduzindo o volume dos poros de maior tamanho. Desse modo, a ocorrência do processo de compactação pode causar deformação dos agregados do solo, reduzindo os poros de maior tamanho, sendo que a quebra dos agregados produz fragmentos que preenchem os macroporos, podendo eventualmente aumentar os microporos ao acaso (STARTSEV; MCNABB, 2001). Esta modificação no sistema poroso do solo resulta na redução na porosidade total e em maiores valores da densidade do solo.

As alterações das propriedades físicas do solo como a densidade e porosidade do solo, bem como, a diminuição dos macroporos, pode afetar significativamente o crescimento das plantas, afetando diretamente a produtividade da cultura (DAUDA; SAMARI, 2002). A compactação do solo pode causar um menor transporte de nutrientes até a raiz da planta, devido a um incremento no escorrimento, reduzindo a água no solo, ocasionando dessa forma uma diminuição do fluxo interno. Podem também impedir o necessário desenvolvimento radicular, por causa do impedimento mecânico imposto às raízes, diminuindo o volume explorado pelas mesmas. Outros problemas associados à compactação refere-se a difusão e trocas gasosas entre o solo e a atmosfera (SHESTAK; BUSSE, 2005). De acordo com Brady & Weil (2002), a difusão de gases é nula quando os macroporos representam menos de 10%.

Existem diversos métodos para se avaliar a compactação do solo. Em alguns destes métodos a avaliação é feita diretamente no campo, como por exemplo, os penetrômetros ou Vane Test, os quais são utilizados para avaliar a resistência do solo à penetração (DIAS JUNIOR et al., 2004) e ao cisalhamento (IORI; DIAS JÚNIOR; SILVA, 2012), respectivamente. Algumas propriedades do solo podem ser usadas como indicativas da compactação do solo, como densidade do solo, porosidade do solo, macroporosidade e permeabilidade (HILLEL, 1982; TAYLOR; BRAR, 1991; NOVAK et al., 1992; WOOD et al., 1993; RICHART et., 2005; GONTIJO et al., 2008).

Outros métodos de avaliação da compactação do solo envolvem análises de laboratório, como por exemplo, a compressibilidade do solo (SILVA et al., 2003b; DIAS JUNIOR et al., 2007; SILVA et al., 2009; AJAYI ET AL., 2010; PIRES et al., 2012; IORI et al., 2012) que é definida como sendo a facilidade com que um solo não saturado decresce de volume quando sujeito a pressões (GUPTA; ALLMARAS, 1987). Para LEBERT; HORN (1991) a compressibilidade depende de fatores externos e internos. Os fatores externos podem ser atribuídos principalmente à energia de compactação aplicada ao solo por meio do pisoteio de animais ou humanos e pelo tráfego de máquinas (SILVA et al., 2003b; SILVA et al., 2009). Os fatores internos são história de tensão (DIAS JUNIOR, 1994), umidade do solo (IMHOFF, 2002; OLIVEIRA et al., 2003), textura do solo (MCBRIDE; JOOSSE, 1996; IMHOFF, 2002), estrutura do solo (LIMA et al., 2006), densidade solo (OLIVEIRA et al., 2003), potencial de água e ligações entre as partículas e agregados (LARSON; GUPTA; USECHE, 1980; DIAS JUNIOR, 1994).

A fim de se avaliar estes efeitos da compactação, Dias Junior & Pierce (1995) utilizaram o ensaio de compressibilidade (ensaio de compressão uniaxial). Este consiste na aplicação de pressões sucessivas e contínuas, previamente estabelecidas, a uma amostra indeformada de material de solo na condição parcialmente saturada.

Deste ensaio obtém-se a curva de compressão do solo (Figura 1), que representa graficamente a relação entre o logaritmo da pressão aplicada e a densidade do solo (DIAS JUNIOR, 1994). Esta curva é obtida em laboratório e tem sido utilizada para simular as reduções do volume do solo (DIAS JUNIOR, 1994; SILVA et al., 2003a; Santos et al., 2009; SILVA et al., 2009; AJAYI ET AL., 2010; PAIS et al., 2011; ARAUJO-JUNIOR et al., 2011; MARTINS et al., 2012). Da curva de compressão do solo obtém-se a pressão de pré-consolidação (σ_p). Existem diferentes métodos de determinação da σ_p (CASAGRANDE,

1936; LEBERT; HORN, 1991; JOSE; SRIDHARAN; ABRAHAM, 1989) e entre estes métodos destaca-se o método proposto por Dias Junior & Pierce (1995).

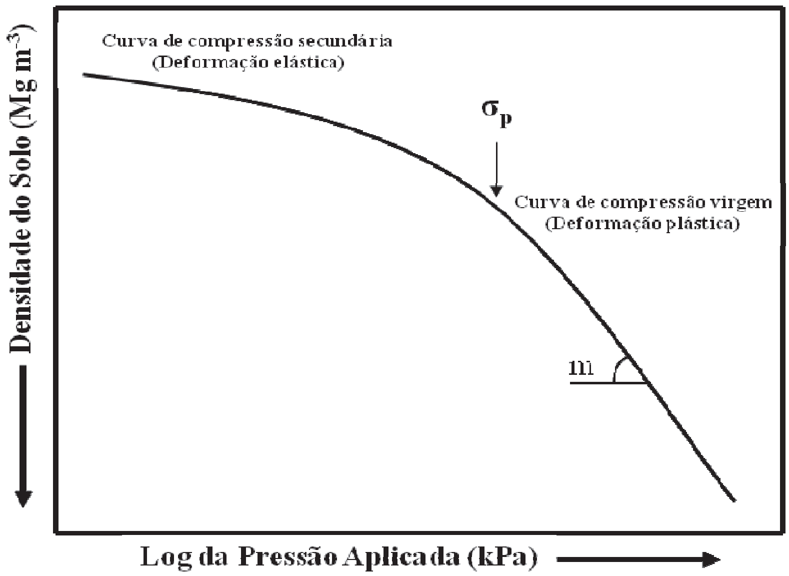

Figura 1 Curva de compressão do solo mostrando a curva de compressão secundária, curva de compressão virgem, pressão de pré-consolidação (σ_p) e o índice de compressão (m) Adaptado de Dias Junior (1994)

Quando o solo não sofreu nenhuma pressão prévia, a relação entre a pressão aplicada e a densidade do solo é linear e qualquer pressão aplicada resultará em deformações não recuperáveis (DIAS JUNIOR; PIERCE, 1996). Porém, quando o solo já teve um histórico de tensão, a curva de compressão apresentará duas regiões, sendo uma região representada pela curva de compressão secundária, onde ocorrem deformações recuperáveis e a curva de compressão virgem onde ocorrem deformações não recuperáveis (DIAS JUNIOR; PIERCE, 1996; LEBERT; HORN, 1991; STONE; LARSON, 1980). A σ_p é a pressão que divide estas regiões e devido a isso tem sido utilizada como um indicador da sustentabilidade da estrutura do solo (DIAS JUNIOR; PIERCE, 1996; HOLTZ; KOVACS, 1981; SILVA et al., 2009; AJAYI ET AL., 2010). Além disso, a pressão de pré-consolidação tem sido utilizada como estimativa da capacidade de suporte de carga do solo e predição da compactação (DIAS JUNIOR et al., 2002; ; SEVERIANO et al., 2009; AJAYI ET AL., 2010; PAIS et al., 2011; ARAUJO-JUNIOR et al., 2011).

2.3 Compactação do solo e a cultura do cafeeiro

As mais diversificadas situações (manejos inapropriados, intensidade de tráfego e umidade inadequada de trabalho, etc.) aplicadas em lavouras cafeeiras tem afetado diretamente a estrutura do solo, causando a compactação do solo, o que diminui fortemente o potencial produtivo destas lavouras.

Estudando o efeito de diversos manejos na sustentabilidade da estrutura de um Latossolo Vermelho cultivado com cafeeiros e avaliando a linha de tráfego em três camadas do solo (0 a 10, 10 a 20, 20 a 30 cm), Miranda et al. (2003) encontraram que os sistemas de cultivo convencional de cafeeiro (com aração e gradagem no preparo do solo por ocasião do plantio) e cafeeiro irrigado (irrigação por pivô central) apresentaram maior capacidade de suporte de carga na camada de 0 a 10 cm. Já o sistema cafeeiro com 3 anos (com aração e gradagem no preparo do solo por ocasião do plantio) apresentou a menor capacidade de suporte de carga, indicando que esse sistema é mais susceptível à compactação do que os outros sistemas para a camada de 0 a 10 cm. Para as demais camadas, os sistemas de cultivo convencional de cafeeiro e cultivo de cafeeiro não convencional (manejo de plantas em livre crescimento) apresentaram maior capacidade de suporte de carga, enquanto os sistemas cafeeiro com 3 anos e cafeeiro irrigado apresentaram a menor capacidade de suporte de carga.

Avaliando os efeitos das operações mecanizadas num Latossolo Amarelo com cafeeiros, Silva et al. (2006) verificaram que os modelos de capacidade de suporte de carga não foram estatisticamente diferentes nas três camadas estudadas (0 a 3, 10 a 13 e 25 a 28 cm). Estes resultados ocorreram devido a uma aração, realizada após o desmatamento em anos anteriores, proporcionando uma homogeneização das camadas em relação à sua capacidade de suporte de carga.

Diferentes locais numa lavoura de café (projeção da saia, entrelinha e linha de tráfego) apresentam comportamentos distintos no que diz respeito à capacidade de suporte de carga. Para isso, Gontijo et al. (2008) desenvolveram modelos de capacidade de suporte de carga em diferentes posições de amostragem na lavoura cafeeira e verificaram que o manejo (história de tensão) se destacou entre os fatores que influenciaram a capacidade de suporte de carga de um solo. Para estes autores, a entrelinha apresentou menor capacidade de suporte de carga em razão do processo de subsolagem realizado meses antes da data de amostragem, apagando toda a história de tensão existente nesse local da lavoura cafeeira. Por outro lado, a linha de tráfego possuiu uma história de tensão induzida pelo tráfego desde a implantação da lavoura, apresentando maior capacidade de suporte de carga. Já a projeção da saia mostrou comportamento intermediário quanto à capacidade de suporte de carga, refletindo a condição inicial de implantação da lavoura cafeeira, visto que sua capacidade de suporte de carga não diferiu da capacidade de suporte de carga do solo sob a mata natural.

Os diferentes sistemas de manejo de plantas invasoras utilizados em lavouras cafeeiras podem alterar atributos químicos, físico-hídricos e biológicos do solo, alterando o comportamento compressivo e, consequentemente, a capacidade de suporte de carga do solo (ARAUJO-JUNIOR; DIAS JUNIOR; GUIMARÃES, 2008; SANTOS et al., 2009; PAIS et al., 2011 e ARAUJO-

JUNIOR et al., 2011). Araujo-Junior, Dias Junior, Guimarães (2008) verificaram que a camada mais suscetível à compactação foi a de 25 a 28 cm do sistema de manejo herbicida de pré-emergência, e a mais resistente, a camada de 0 a 3 cm deste mesmo sistema de manejo. Os sistemas de manejo sem capina e herbicida de pós-emergência nas camadas de 0 a 3, 10 a 13 e 25 a 28 cm, capina manual nas camadas de 0 a 3 e 25 a 28 cm e herbicida de pré-emergência na camada de 10 a 13 cm apresentaram a mesma resistência à compactação.

Por outro lado, Santos et al. (2009) constataram que os métodos de controle, herbicida de pré-emergência; associados à condição sem capina e à roçadora; a capina manual, associada à sem capina, nas entrelinhas, apresentaram maior resistência à compactação. Os métodos roçacarpa, associados à roçadora; o herbicida de pré-emergência, associado à enxada rotativa; e o herbicida de pré- emergência e roçacarpa, associados à grade de discos nas entrelinhas, apresentaram maior suscetibilidade à compactação do solo.

Da mesma forma, avaliando a compactação causada pelo manejo de plantas invasoras em Latossolo Vermelho-Amarelo cultivado com cafeeiros, Pais et al. (2011) verificaram que os manejos grade de discos, roçadora e trincha foram os manejos que promoveram maior compactação e que os manejos com braquiária, crotalária e soja foram os que causaram menor. Araujo-Junior et al. (2011) verificaram para um Latossolo Vermelho distroférrico típico que o manejo de plantas invasoras utilizando grade e herbicida de pré-emergência favorece a formação do encrostamento superficial, os incrementos nos valores de densidade do solo e capacidade de suporte de carga na profundidade de 0 a 3 cm.

O tempo de implantação da cultura cafeeiro é outro fator que afeta a estrutura do solo. Martins et al. (2012) verificaram que o uso dos modelos de capacidade de suporte de carga permitiu identificar a suscetibilidade do solo à compactação, em razão do tempo de implantação da lavoura cafeeira. Estes autores verificaram também que a porcentagem de amostras compactadas aumentou com a idade da lavoura na camada de 15 a 18 cm.

2.4 Declividade do terreno influenciando a alteração nas propriedades físico-mecânicas do solo

Estudos em ciência do solo relacionados à declividade do terreno, geralmente sempre são associados à perda de solo, pois, quanto mais elevada for a declividade de um solo, maior será a velocidade com que a água irá escorrer sobre este solo, promovendo consequentemente, maior erosão do solo.

A declividade de um solo pode influenciar as alterações físico-mecânicas do solo, principalmente quando associado ao tráfego agrícola. Gontijo et al. (2007) realizaram o planejamento amostral da pressão de pré-consolidação em um Latossolo Vermelho distroférrico e identificou que a declividade influenciou indiretamente a pressão de pré-consolidação, por meio da umidade do solo. O mapa de isolinhas de σ_p obtido por estes autores permitiu observar zonas de maior e menor suscetibilidade à compactação, possibilitando a tomada de decisão sobre onde começar a trafegar sem causar problemas adicionais à estrutura do solo.

A densidade do solo é outra propriedade que pode ser influenciada pela declividade e tráfego agrícola. Estudando o efeito do tráfego de máquinas em terrenos com diferentes declividades, NAJAFI; SOLGI; SADEGHI (2010) encontraram maiores densidades do solo nos terrenos com maiores declividades. Na comparação entre terrenos com declividades menores que 10% e com declividade entre 10 e 20% não houve diferenças significativas, porém locais com declive maior que 20% apresentaram diferenças significativas na densidade do solo em relação às outras duas classes de declividades. Verificaram ainda, que a quantidade de passadas das máquinas, ou seja, a intensidade de tráfego acentuou ainda mais o problema da densidade do solo em relação ao declive. Para estes autores o aumento da densidade do solo nas trilhas das encostas mais íngremes pode ser associado ao aumento da carga no eixo traseiro e a patinagem da máquina no sentido da encosta. Similarmente, Davies; Finney; Richardson (1973) e RAGHAVAN; MCKYES; BEAULIEU (1977) verificaram que a patinagem afetou diretamente a estrutura do solo e promoveu alterações das propriedades físicas do solo até grandes profundidades.

Avaliando o desempenho operacional de um trator numa área inclinada lateralmente, Leite et al. (2011) verificaram que a patinagem das rodas aumentou com o aumento da inclinação lateral da pista (declividade da área) para todos os tratores usados. Estes autores verificaram que houve uma redução significativa da força de tração com o aumento da inclinação, o que pode ser atribuído a uma transferência de peso lateral.

A inclinação de um terreno é um fator importante e que afeta diretamente a eficiência e custo operacional, além de poder causar a compactação do solo e acelerar o processo de erosão (JAMSHIDI et al., 2008). Estes autores não encontraram diferenças na compactação do solo entre lugares planos e com gradiente longitudinal ou inclinação transversal, salientando que isso foi surpreendente, pois se esperava que o tráfego ao longo de linhas de tráfego planas, teria menor compactação, a linha de tráfego com inclinação transversal teria compactação intermediária, e as linhas de tráfego com gradiente longitudinal teria a maior compactação. Estes autores citaram ainda que essa hipótese foi baseada na distribuição de carga desigual entre os pneus, o que resultaria em maior pico de carga dinâmica sendo exercida sobre o solo.

Por outro lado, NAJAFI; SOLGI; SADEGHI (2009) verificaram diferença entre a porosidade do solo entre terrenos com inclinação menor que 20% e aqueles com mais de 20%, e explicaram que estas diferenças provavelmente poderiam ser explicadas pela maior compactação do solo no terreno mais íngreme e que a diminuição da porosidade pode ser associada à menor velocidade do maquinário agrícola em declives maiores. Quando o maquinário passa mais lento em terreno mais íngreme causa maior distúrbio em comparação ao terreno mais plano. Leite et al. (2011) verificaram que a maior velocidade dos tratores analisados foi obtida nos locais de menor inclinação e que a velocidade mais baixa foi obtida em terrenos com maior inclinação. Portanto, a identificação e a consideração da declividade do terreno no planejamento de operações mecanizadas, pode ser uma consideração importante para proteção do solo.

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SEGUNDA PARTE – ARTIGOS

ARTIGO 1: INFLUENCE OF TERRAIN CONFIGURATION AND ESTABLISHMENT TIME ON PHYSICAL PROPERTIES OF A RED-YELLOW LATOSOL PLANTED WITH COFFEE

(Preparado de acordo com as normas da Revista Brasileira de Ciência do Solo)

SUMMARY

Several factors cause changes in soil hydro-physical properties in modern agriculture. Times of establishment of the culture (plantation age) and the field slope are examples these factors that can influence the extent of damage to soil structure. The objective of this study was to analyze in coffee plantations with different ages of establishment and land slope, the effect of machine traffic on the soil hydro-physical properties. The coffee plantation have a uniform soil type; Red-Yellow Latosol and were aged 2, 7, 18 and 33 years. In these coffee plantations were selected areas with side slope of 3, 9 and 15 %. The soil was sampled at three positions on the coffee row (bottom of traffic line, inter-row and top of traffic line) and at two layers (topsoil and sub-surface). Changes were investigated on the total porosity, macroporosity, microporosity, organic matter, bulk density and aggregate stability. The study showed that among the factors, the establishment time (coffee age) was the factor that affected most of the soil properties. Field slope influenced reasonably the soil physical properties, particularly organic matter, microporosity and aggregate stability. The samples from the inter-row were the best in terms of the preservation of soil structure than samples from traffic lines (bottom and top traffic line) and samples from the bottom traffic line showed better results in terms of soil structure preservation than those from the top traffic line.

Index Terms: agricultural traffic; *Coffea Arabica L.*; soil degradation; aggregate stability.

RESUMO: DECLIVIDADE DO SOLO E IDADE DE CAFÉ NAS PROPRIEDADES FÍSICAS DE UM LATOSSOLO VERMELHO AMARELO

O objetivo deste estudo foi analisar em áreas de cultivo de café com diferentes idades, o efeito do tráfego de máquinas sobre as propriedades físicas de um Latossolo Vermelho-Amarelo em diferentes pontos de diferentes declividades. O estudo foi realizado em plantações de café com 2, 7, 18 e 33 anos de cultivo, agrupados em três classes de declividades do solo. O solo foi coletado em três posições na entrelinha de café (linha de tráfego de baixo, entrelinha e linha de tráfego de cima) e em duas camadas (superficial e sub-superficial). A entrelinha apresentou os melhores valores para os atributos estudados. Entre as amostras da linha de tráfego, as linhas de tráfego de baixo mostrou resultados melhores do que linha de tráfego de cima, devido principalmente à diferença de cobertura vegetal acumulado, que influenciou no teor de matéria orgânica. A declividade da área influenciou razoavelmente as propriedades físicas do solo, especialmente, matéria orgânica, microporosidade e a estabilidade de agregados. As camadas estudadas influenciaram principalmente nos resultados para matéria orgânica e estabilidade de agregados. Dentre os fatores estudados, o tempo de cultivo foi o fator que mais afetou as propriedades do solo.

Termos de indexação: *Coffea Arabica* L., degradação do solo, estabilidade de agregados, tráfego agrícola.

INTRODUCTION

Due to its growing mechanization, the Brazilian agriculture system has in recent past recorded significant progress thereby contributing to significantly to economic development. The trend is likely to continue particularly in coffee culture, which currently ranks fifth in agribusiness exports, contributing US$8.7 billion to the economy (MAPA, 2012). The highest proportions of the coffee farms are found in the southern part of Minas Gerais State, which is still the largest coffee producing area in the country (Rangel et al., 2008). It is noteworthy that while the mechanization of agriculture in Brazil had improved the productivity from farming operations, it has also brought remarkable structural degradation of the soil (Silva et al., 2009). In the Brazilian coffee crop management, all the production stages including weeding, fertilizer application and harvesting are mechanized. In these operations, the narrow strips of land between the rows of coffee tree are repeatedly subjected to traffic of machines and equipment, thereby increasing their susceptibility to soil compaction. This problem is exacerbated in older coffee plantations.

Soil compaction, induced by the high traffic intensities can cause damage to the soil structure, thereby reducing the production potential of coffee plantation (Gontijo et al., 2008). Several soil-dependent conditions can exacerbate the changes in soil physical properties due to agricultural traffic. For example, machine traffic in coffee culture under unregulated soil moisture conditions can be worrisome (Miranda et al., 2003). In addition to the soil moisture conditions, the gradient of the farmland had been observed to alter the effect of machine traffic on the physical and mechanical properties of soils. Jamshidi et al. (2008) noted that in hilly terrain, the load distribution is uneven between tires, which results in a higher peak dynamic load exerted on the ground. Najafi et al. (2009) also found out that the surface impact of vehicle wheels changes with the ground slope even at the same traffic intensity. They further mentioned that during the slippage in steepy terrain, the load is applied unevenly on increasing the revolving axis and the impact on the ground under this axis changes. Similarly, Krag et al. (1986) found that during the harvesting of timber, the slope moderate the stress distributions. The impacts were higher on slopes above 20% that on terrain with slopes less than 20%.

In this study, our hypothesis is that the ground slope of the coffee plantations will influence the location of the center of gravity of operating machine, thereby resulting in differentiated impact and effect on stress distribution in soil under a given machine axis and along the wheel track. Since the time of cultivation of a particular culture can exacerbate this effect due to residual stress effect on the trafficked area, the objective of this study was to analyze in coffee plantation with different establishment times, the effect of machine traffic on the soil physical properties in clayey Red-Yellow Latosol planted to coffee at different side slopes.

MATERIAL AND METHODS

The study was conducted in coffee plantations located in Três Pontas County, South of Minas Gerais State, Brazil (24°26' S; 47°49' W'; altitude of 905 m). This region presents predominant relief of undulating topography. The climate according to Koppen is Cwa, that is, altitude tropical, with an average annual temperature of about 18° C. The average annual rainfall is 1,300 mm with the highest concentration in the months from December to February. The soil of the study area was classified as a Red-Yellow Latosol (Oxisol) clayey texture (Embrapa, 2006) with 510 g kg^{-1} of clay, 200 g kg^{-1} of sand and 290 g kg^{-1} of silt, and particle density of 2.62 Mg m^{-3}.

According to farm history records, prior to the installation of the coffee plantations, the soil was disk - plowed to a 40 cm depth and thereafter harrowed. All equipment used in the coffee crop management was pulled by a Massey

Ferguson 265 tractor, with a mass of about 3,940 kg. the equipment pulled for the farming operations are: fertilizer miname, with approximate mass of 210 kg (3 passes per year), spray jet Arbus 400 Jacto with 400 L capacity and mass of 230 kg (3 passes per year), mower Kamaq with a mass of 340 kg (3 passes per year) and the spray jet PH 400 with 400 L capacity and mass of 210 kg (2 passes per year). The combined total number of passes per year equal to 11 on the same traffic line for each plot at different establishment times.

This study was conducted in coffee plantations with 2 years (planted in 2008 with spacing 3.5 m x 0.7 m – Cultivate Mundo Novo), 7 years (planted in 2003 with spacing 3.5 m x 0.9 m – Cultivate Paraíso MG), 18 years (planted in 1992 with spacing 3.5 m x 1.0 m – Cultivate Mundo Novo) and 33 years (planted in 1977 with spacing 3.5 m x 2.0 m – Cultivate Catuaí Amarelo) of establishment (E). In these coffee plantations were selected areas (coffee row) with side slope of 3, 9 and 15% (S). The soil were sampled (P) at three positions on the coffee row (Figure 1): bottom of traffic line (B), inter-row (I) and top of traffic line (T) at two layers (D): 0.00 m – 0.03 m (topsoil) and 0.15 m – 0.18 m (sub-surface). Thus, samples were collected from these seventy two (72) conditions (4 establishment times x 3 slopes x 3 positions x 2 depths), with three repetitions, totaling 216 soil samples.

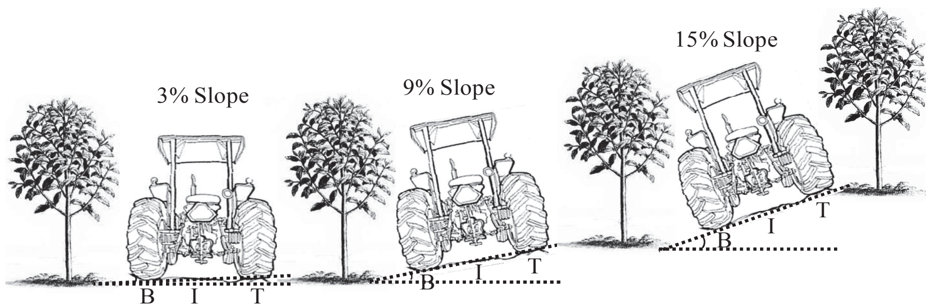

Figure 1. Schematic representation of the sampling points in the coffee row with three side slopes (3, 9 and 15% slope). B: bottom traffic line, I: inter-row and T: top traffic line.

Representative samples based on the varied sampling criteria were used for various physical characterizations as described below. The texture was determined by the pipette method (Day, 1965). The particle density was determined by the pycnometer method (Blake & Hartge, 1986a). Bulk density (BD) based on the volumetric ring was determined following the methodology of Blake & Hartge (1986b). Total porosity (TP) was calculated using the expression:

$$TP = [1 - (BD.PD^{-1})]100 \quad \text{(eq. 1)}$$

Where, TP – total porosity (m^3 m^{-3}), PD – particle density (Mg m^{-3}) and BD – bulk density (Mg m^{-3}). The microporosity (Mi) was determined with soil sample by tension -6 kPa (Embrapa, 1997) and macroporosity (Ma) was determined based on the expression:

$$Ma = TP - Mi \quad \text{(eq. 2)}$$

Where, Ma – macroporosity (m^3 m^{-3}), TP – total porosity (m^3 m^{-3}) and Mi – microporosity (m^3 m^{-3}). Organic matter (OM) was analyzed following the standard procedures (Embrapa, 1997) and was determined using the wet combustion method. The stability of aggregates was determined by screening in water, with a set of sieves 2, 1, 0.5, 0.25 and 0.105 mm, and the geometric mean diameter (GMD) determined according to Schaller & Stockinger (1953). Significant differences in soil attributes were identified using ANOVA F-test and Scott and Knott test at 5% level using the SISVAR computer software (Ferreira, 2000).

RESULTS AND DISCUSSION

Table 1 presents ‘F’ values in the analysis of variance of organic matter (OM), total porosity (TP), macroporosity (Ma), microporosity (Mi), bulk density (BD) and aggregate stability by geometric mean diameter (GMD) for years of establishment (E), land slopes (S), sampling positions (P) and depths (D) effects. The analysis of variance showed that effects as establishment time and sampling position were significant at all levels for all studied variables. Depth effect was only not significant for TP. And slope factor was significant for OM, Mi and GMD. The level of significance of each factor was different for the six studied variables. The establishment time of the coffee plantation was the most important factor affecting TP and BD. Depth was most important factor that affected OM and GMD. For Ma and Mi, the sampling position was most important factor. For OM, almost all interactions were significant, just DxExP interaction was not significant. For TP, E and P factors was significant and DxE, DxP and DxExSxP interactions were significant. E, P and D factors was significant and PxE, DxE and DxP interactions were significant for Ma. For Mi only DxE, DxP, DxExS and DxExSxP interactions were not significant. For BD, E, P and D factors was significant and PxE, DxP, DxExP and DxExSxP interactions were significant. For the end, DxS and DxP interactions were not significant for GMD.

Table 1. 'F' values in the analysis of variance for organic matter (OM), total porosity (TP), macroporosity(Ma), microporosity (Mi), bulk density (BD) and stability of aggregates by geometric mean diameter (GMD) for different establishment time of the coffee plantation (E), slopes (S), sampling positions (P) and depth (D) in Red-Yellow Latosol.

Sources of variation	DF	OM	TP	Ma	Mi	BD	GMD
E	3	81.8**	40.8**	10.9**	33.0**	36.7**	33.7**
Error (a)	8						
S	2	7.3*	0.4^{NS}	3.0^{NS}	5.4*	0.4^{NS}	24.0**
E x S	6	18.2**	1.1^{NS}	3.3^{NS}	7.7*	0.9^{NS}	24.4**
Error (b)	6						
P	2	24.4**	17.0**	30.2**	50.2**	28.7**	87.5**
P x E	6	11.4**	3.3^{NS}	5.4**	5.8*	4.5*	59.2**
P x S	4	10.1**	1.6^{NS}	1.5^{NS}	9.6**	1.7^{NS}	18.6**
P x E x S	12	4.5*	1.0^{NS}	2.1^{NS}	16.9**	1.1^{NS}	33.0**
Error (c)	6						
D	1	2013**	0.4^{NS}	11.5**	28.4**	9.3**	200**
D x E	3	47.0**	5.0**	3.6*	2.4^{NS}	2.4^{NS}	3.0*
D x S	2	4.2*	0.6^{NS}	0.4^{NS}	4.2*	0.4^{NS}	0.7^{NS}
D x P	2	13.4**	15.7**	11.8**	1.7^{NS}	9.9**	2.3^{NS}
D x E x S	6	12.8**	1.5^{NS}	0.8^{NS}	1.2^{NS}	1.5^{NS}	13.2**
D x E x P	6	2.1^{NS}	1.9^{NS}	1.7^{NS}	3.2**	2.7*	15.2**
D x S x P	4	7.6**	0.2^{NS}	1.8^{NS}	4.0**	0.4^{NS}	9.8**
D x E x S x P	12	2.7**	3.2**	1.6^{NS}	1.3^{NS}	3.1**	7.6**
Error (d)	124						
CV *(a)* %		8.5	5.0	25.2	4.5	6.0	6.1
CV *(b)* %		9.0	6.2	20.0	4.1	6.6	4.9
CV *(c)* %		7.5	6.5	21.4	2.2	6.5	5.7
CV *(d)* %		9.5	4.4	21.4	4.8	4.7	8.1

DF: Degrees of freedom, **: Significant at 1% level, *: Significant at 5% level and NS: not significant. CV: Coefficient of variation.

All establishment times were significantly different from each other for OM (Table 2). The values followed the order: 18>7>2>33 years old. The highest values of OM were observed in the plane areas (3%), while the steeper areas (9 and 15%) had similar values but lesser values than the 3% slope. It was observed in plane areas the higher OM accumulation; because these areas hadn't problems with soil erosion and loss water, consequently, smaller loss of OM, because these problems frequently occur in steeper areas (9 and 15%). The distinct positions analyzed had values different for OM of each other, with bottom traffic line having the highest value, followed by inter-rows and top traffic line. These results are disagreeing with Gontijo et al. (2008), which found similar values of OM between inter-rows and traffic line. When it was evaluated at different depths, the main attribute with distinct behavior is the organic matter. The topsoil had higher values of OM (Table 2) than the sub-surface. Silva et al. (2006), studying a Latosol with coffee plant also observed significant difference in OM values between topsoil and sub-surface. OM causes changes in almost all other soil physics attributes. Rangel et al. (2008) also found highest OM values in the 0-0.05 m layer of soil with coffee plant. As it was observed higher values for OM in topsoil, the other soil attributes (TP, Ma, Mi, BD and GMD) also will have "good" values. In many soils, the organic matter is the agent main responsible for aggregates formation and stability. Organic matter can stabilize soil structure and makes it more resistant to degradation (Cochrane & Aylmore, 1994), and decreases bulk density and soil strength (Carter, 2002, Iori et al. 2012a). Hamzaa & Anderson (2005) identified the most commonly reported mechanisms as by which organic matter influences soil structure and compactibility to include: (a) binding soil mineral particles (Zhang, 1994); (b) reduction of aggregate wettability (Zhang & Hartge, 1992); and (c) influencing the mechanical strength of soil aggregates, which is the measure of coherence of inter-particle bonds (Quirk & Panabokke, 1962).

Table 2. Mean values of organic matter (OM), total porosity (TP), macroporosity (Ma), microporosity (Mi), bulk density (BD) and stability of aggregates by geometric mean diameter (GMD) for different establishment time of the coffee plantation (E), slopes (S), sampling positions (P) and depths (D) in Red-Yellow Latosol.*

Factor level	OM ($g\ kg^{-1}$)	TP ($m^3\ m^{-3}$)	Ma ($m^3\ m^{-3}$)	Mi ($m^3\ m^{-3}$)	BD ($Mg\ m^{-3}$)	GMD (mm)
E (Years)						
2	34.1 C	0.51 C	0.14 B	0.37 B	1.28 B	3.59 C
7	36.9 B	0.52 B	0.14 B	0.38 A	1.22 C	3.83 B
18	40.0 A	0.55 A	0.18 A	0.37 B	1.19 C	3.91 B
33	31.3 D	0.50 D	0.15 B	0.35 C	1.33 A	4.03 A
S (%)						
3	36.7 A	0.52 A	0.15 A	0.37 A	1.26 A	3.95 A
9	35.1 B	0.52 A	0.16 A	0.36 A	1.25 A	3.73 C
15	34.8 B	0.52 A	0.15 A	0.37 A	1.26 A	3.84 B
P						
Top	34.1 C	0.51 B	0.14 B	0.37 B	1.29 A	3.60 C
Inter-row	35.4 B	0.54 A	0.18 A	0.36 C	1.20 B	4.08 A
Bottom	37.2 A	0.51 B	0.14 B	0.38 A	1.28 A	3.84 B
D						
Topsoil	45.8 A	0.52 A	0.14 B	0.37 A	1.25 B	4.14 A
Sub-surface	25.3 B	0.52 A	0.16 A	0.36 B	1.27 A	3.54 B

* Mean values for each factor were obtained by averaging the measured values over the levels of the other three experimental factors. Values followed by different letters in each column are significantly different at the 5.0% level by

Scott and Knott test. Number of experimental points is 216 representing a split plot experiment with 4 establishment times of the coffee plantation, 3 slopes, 3 sampling positions and 2 depths with 3 replications.

Coffee plantation with 18 years of establishment had higher values for TP and Ma (Table 2) than others areas. For Ma, the values were similar for establishment time (2, 7 and 33 years). It was also noted that there were no statistical differences between the different side slopes analyzed for TP and Ma (Table 2). Najafi et al. (2009) working in the northern mountainous forest of Iran, also found TP values were similar on 9 and 15% slope. For sampling position, the highest values for TP and Ma were observed in inter-rows than in different traffic lines (top and bottom traffic line), that presented similar values (Table 2). The greater deformation on soil structure was observed in traffic lines due the trafficking of machine in the coffee plantations, for other hand, inter-rows position did not have disturbance due no traffic in these places. Gontijo et al. (2008) also found biggest values for TP and Ma at inter-rows in relation line traffic. It was observed similar values for TP between depths (Table 2). The over-compacted soils are generally found in the wheel tracks, with the effects more marked on topsoil (Balbuena et al., 2000). There is evidence that topsoil compaction is related to ground pressure (Hamzaa & Anderson, 2005).

In the literature, Ma value range between 0.10 to 0.15 m^3 m^{-3} had been considered as the critic range. In this range, water infiltration and root aeration for the coffee plant is affected (Cockroft & Olsson, 1997), because most plants grown satisfactory when macropores are higher (Kiehl, 1979; Gupta & Allmaras, 1987). Thus considering this range as critical, just areas with 18 years of establishment presented Ma value higher this range. Between sampling positions, just inter-rows had Ma value higher this range. Without in this critic range, remain just soil in surface (topsoil) and areas with 9% slope.

The minor coefficient of variation in this study was observed for soil micropores (Table 1). Mi values (Table 2) had similar behavior between side slopes analyzed. The establishment time, sampling position and depth factor had different responses. Areas with 7 years had more amounts of micropores, followed by areas with 2 and 18 years old. The minor proportions micropores were observed on areas with 33 years old. For depths, the topsoil had higher values than the sub-surface (Table 2). This is likely because, some of the macropores changed to micropores due the trafficking of tractors. Dias Junior (2000) had showed that pores distribution can be modified due compaction caused by tractor traffic. Gontijo et al. (2008) further showed that the decrease of macropores is due to a collapse of the soil structure, due to excessive force applied on the soil principally on traffic line. The collapse soil structure produces fragments that occupied macropores, creating an additional space of micropores (Startsev & McNabb, 2001). For sampling positions, the traffic lines had higher micropores values than inter-rows. For traffic lines, the bottom traffic line presented higher micropores values than top traffic line. Gontijo et al. (2008) also found higher values for Mi in line traffic than the inter-rows, but these authors did not discriminate the position of the traffic line (bottom or top traffic line).

It was found out that the mean BD values for the different establishment time of the coffee plantation were distinct from each other (Table 2), with the 33 years old plantation having higher values implying highest soil strength (Iori et al. 2012b). The lowest value for BD was observed in the areas with 7 and 18 years old coffee, followed by area with the 2 years old coffee. Field slope as a factor did not have influences on the BD (Table 1). On the other hand, sampling position factor had influences on the BD, with the inter-rows having the lowest values and bottom traffic line and top traffic line showing similar values. Other factor that had influences on the BD was the depths of sampling. For this factor, it was found the lowest values in topsoil. The BD behavior was similar to the behavior of the OM. Ekwue (1990) had found a relationship between bulk density and organic content significant at 1% levels. Macrae & Mehuys (1985) showed that organic matter reduces bulk density by soil dilution and improvement in aggregate stability.

The improvement in aggregate stability due OM, also was observed in this study. The highest OM values in topsoil also resulted in highest GMD values in this same layer (Table 2). And this is because the OM has a strong effect in soil aggregation, thus higher OM values in a place will be probably translate to more soil aggregation (Ekwue, 1990), resulting in higher GMD. Organic matter is an important factor in soil aggregation (Seifert et al., 1998). Tisdall & Oades (1982) suggested a positive correlation between organic matter content and aggregate stability. And Boix-Fayos et al. (2001) did not observe a positive correlation between organic matter and microaggregation, but showed the stability of the macroaggregates was positively associated with organic matter content. Along the areas of tractor traffic, the bottom traffic had a higher value and different value than top traffic line. For side slopes, the highest values for GMD were observed for area with side slope of 3%, followed by the area with side slope of 15 and 9%. For time of establishment, the highest values of GMD was found in oldest plantation (33 years), decreasing as the plantation age reduces (Table 2).

The relationship between OM, BD and Ma and time since the establishment of the coffee plantation is well fitted by a quadratic regression curve for the three sampling positions studied (Figure 2). At all the three sampling positions (bottom of traffic line, inter-row and top of traffic line) the OM and Ma increased with time of establishment up to a certain time of establishment beyond which the OM and Ma began to decrease with the increase in the time of establishment. Also at all the three sampling positions, the BD decreased with time of establishment up to a certain time of establishment beyond which the BD increased with the increase in time of establishment. Based on the regression analysis, maximum OM and Ma and minimum BD were 42 g kg^{-1}, 0.20 m^3 m^{-3} and 1.12 Mg m^{-3}, respectively, all which occurred when the establishment time is about 18 years. The lowest and highest values for BD and Ma, respectively, were observed in the inter-rows. This is because the inter-rows is not directly trafficked by tractor wheel, thus the soil structure was more preserved. For OM the highest values was observed on the bottom traffic line. During the field trials, it was observed the bottom traffic line was always covered with fresh vegetation. The accumulation of vegetation at the bottom traffic line had two consequences on the soil; increased OM values over the years and lower structure degradation as observed in this study. On the other hand, at the top traffic line the soil exposed causing more soil structure degradation. The increase OM contents with increased establishment time of the coffee plantation until 18 years old (Figure 2), may indicates that the OM content increases until a certain cultivation time threshold is reached; after this time the OM content begin to decrease. In the tropical region, where this study was conducted, the general trend of high temperature, rainfall results in faster rate of microbial activity which causes rapid decomposition of organic materials into the soil (Longo & Espíndola, 2000). Since OM contents in cultivated area depends mainly on the rate of addition by waste and intensity of the decomposition process of the OM (Rangel et al., 2008), the reduced addition of the waste in this old plantation promoted the observed decreased OM.

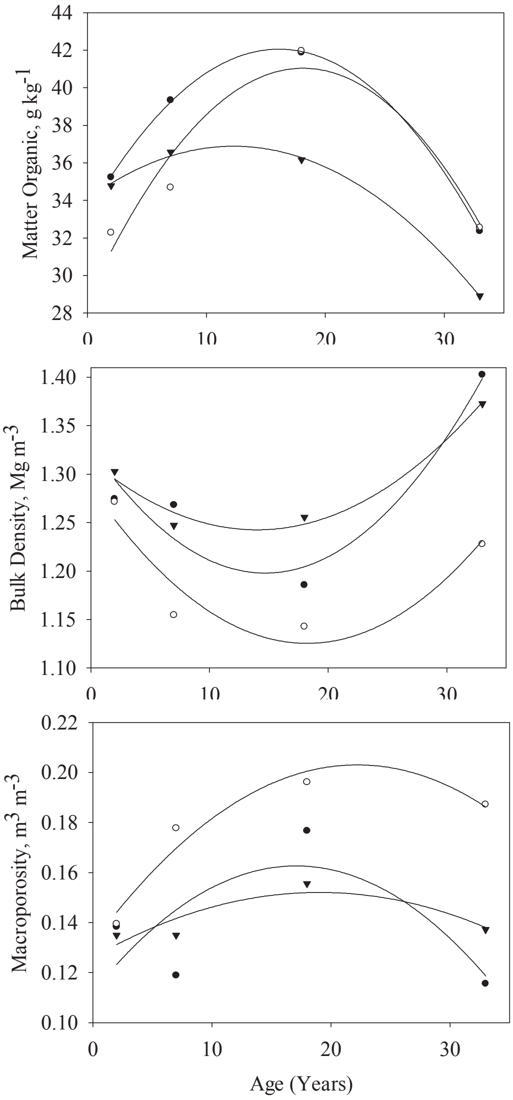

Figure 2. Effect of the interaction between establishment time and sampling position on organic matter, bulk density and macroporosity (data are means of all three slopes and two depths). ▼ Top traffic line, ○ Inter-row and ●Bottom traffic line.

In Figure 3 it was presented the linear relation between side slope degree with OM, GMD (stability of aggregates) and the Mi for the different sampling positions. The side slope and sampling position exhibited similar behavior for OM, GMD and Mi. The increases of slope degree increased the Mi at for the inter-row and the bottom of the traffic line. On other hand the OM decreased at the top and bottom of the traffic line with increases in slope steepness. This was similarly observed on the GMD (stability of aggregates) at the top of the traffic line. This probably results from the differential pressure on the inclined plane during tractor traffic. This caused more compaction leading to more aggregation in soil and consequent organic matter degradation.

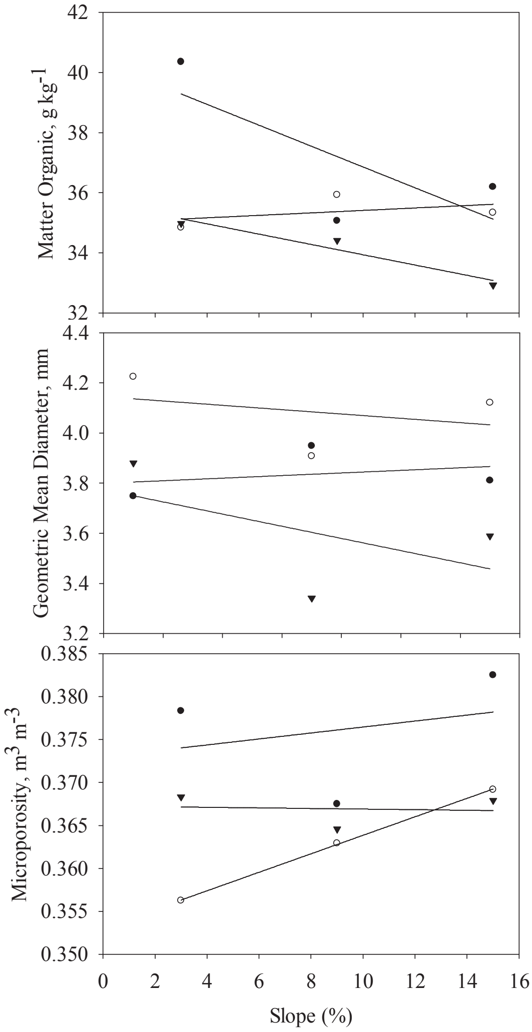

Figure 3. Effect of the interaction between slope and sampling position on organic matter, stability of aggregates by geometric mean diameter and microporosity (data are means of all four establishment time and two depths). ▼ Top traffic line, ○ Inter-row and ●Bottom traffic line.

Other interaction observed in this study was between the time of establishment and the depth for OM, BD and Ma (Figure 4). It was obtained a similar trend to what was observed in figure 2, with the parameters curves attaining the peak around 18 years. After this, the OM and Ma values decreased while the BD values increased. The topsoil presented small values for BD. For OM and Ma the highest values was obtained on the topsoil. OM had the most accentuated difference between depths for all the establishment time of the coffee plantation studied. However, the BD in the first few years (2 and 7 years of establishment) presented had similar values, but the differences increased with the establishment time cultivation. On the other hand, the Ma showed more difference between the depths in first years of cultivation. Already areas with 33 years of establishment had the same result between depths. Therefore, the time of cultivation tended to provide homogeneity between layers for Ma. As the establishment time of the coffee plantation increases, there are more alteration soil physical attributes. This could be linked to the residual effect on the soil layers due the accumulation of agricultural traffic, causing degradation of the soil structure. This had been similarly reported by Silva et al. (2006) and Wood et al. (1993). Martins et al. (2012) also found the same result while studying soil physical behavior in coffee plantation with different ages. The result showed that the percentage of compacted soil samples increases with the age of the coffee plantation.

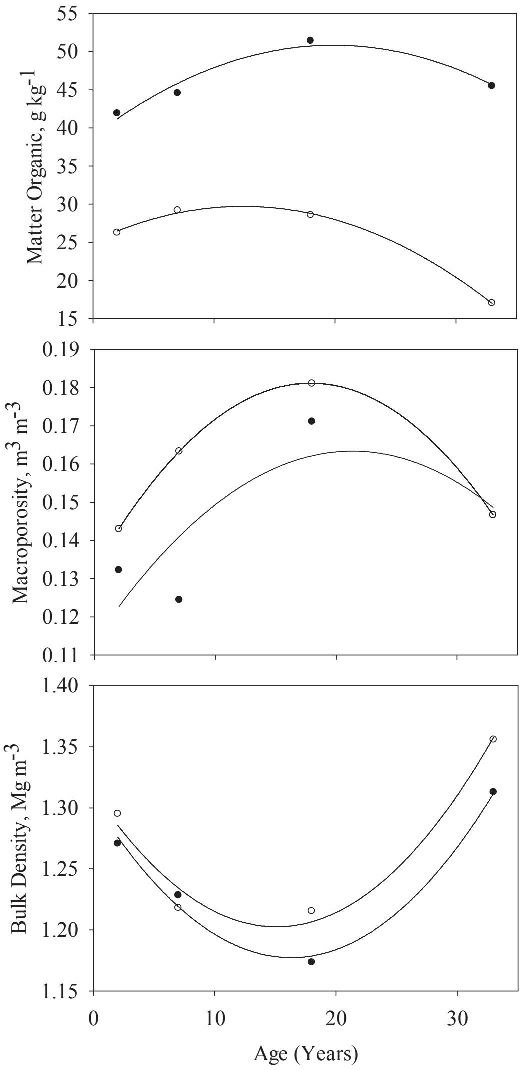

Figure 4. Effect of the interaction between establishment time and depth on organic matter, macroporosity and bulk density (data are means of all three slopes and three sampling positions). ●Topsoil and ○ Sub-surface.

Table 3 presents the results of the interaction between sampling position and depth for OM, TP, Ma and BD. For OM, it was observed difference between depths for all sampling positions. But when it was analyzed the behavior of OM in each depth, it were found differences between sampling positions. When only the layer analyzed was topsoil, it was observed highest values in bottom traffic line followed by inter-row and top traffic. When the layer analyzed was the sub-surface, it was observed highest values at the traffic lines while the inter-row had lowest values of OM. The observed difference along the traffic line traffic already discussed. The higher level of OM observed at the bottom traffic line could be linked possibly to the accumulation of vegetation there. Also it was found similar values of BD, between depths, at the bottom traffic line and top traffic line, but in the inter-row there was difference between depths. The similarity between depths in the traffic line was due applied pressure by agriculture machines. It was observed the same behavior between sampling positions for both analyzed layers (topsoil and sub-surface) for BD, and only at the topsoil for TP and Ma; with the traffic lines (bottom and top) presenting similar values, while inter-row had lower values than traffic lines. Topsoil presented lower Ma values than sub-surface for both traffic lines, already inter-row presented similar Ma values between depths.

Table 3. Mean values of organic matter (OM), total porosity (TP), macroporosity (Ma) and bulk density (BD) for different sampling positions and depth in Red-Yellow Latosol.

Depth	Sampling position		
	T	I	B
		Organic Matter (g kg^{-1})	
Topsoil	42.7 Ac	46.5 Ab	48.3 Aa
Sub-surface	25.5 Ba	24.2 Bb	26.1 Ba
		Total Porosity (m^3 m^{-3})	
Topsoil	0.50 Bb	0.55 Aa	0.51 Ab
Sub-surface	0.52 Aa	0.53 Ba	0.52 Aa
		Macroporosity (m^3 m^{-3})	
Topsoil	0.12 Bb	0.18 Aa	0.12 Bb
Sub-surface	0.16 Aa	0.17 Aa	0.15 Aa
		Bulk Density (Mg m^{-3})	
Topsoil	1.30 Ab	1.16 Ba	1.28 Ab
Sub-surface	1.29 Ab	1.24 Aa	1.28 Ab

Means with the different lower-case letter in each row and with the different capital letter in each column for each soil attribute are significantly different at the 5.0% level by Scott and Knott test.

CONCLUSIONS

1. The study showed that among the factors, the establishment time of the coffee plantation was the factor that affected most of the soil properties (total porosity, macroporosity, microporosity, bulk density, organic matter and geometric mean diameter).

2. The establishment time of the coffee plantation had a quadratic relation (curve model) for most soil parameters studied, with peak of the curve at around

18 years; signifying that coffee cultures improved the e the hydro-physical properties of the soil to till 18 years, thereafter the degradation of the soil structure sets in.

3. The samples from the inter-row were the best in terms of the preservation of soil structure among the studied sampling points. Samples from the bottom traffic line (wheel track) showed better results in terms of soil structure preservation than those from the top the traffic line, mainly due to difference in accumulated vegetation cover influencing organic matter content.

4. Side slope influenced reasonably the soil physical properties, particularly organic matter, microporosity and aggregate stability.

5. Organic matter and aggregates stability varied at the studied depths with high impact of traffic observed at the topsoil.

ACKNOWLEDGEMENTS

We sincerely appreciate the “Consórcio Brasileiro de Pesquisa e Desenvolvimento do Café CBP&D/Café” and CAPES, FAPEMIG and CNPq for financial support for the research.

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ARTIGO 2: COMPARISON OF FIELD AND LABORATORY OF THE LOAD BEARING CAPACITY IN COFFEE PLANTATION

Comparação de modelos de capacidade de suporte de carga do solo obtidos com umidade de campo e laboratório em áreas cafeeiras

(Preparado de acordo com as normas da Revista Ciência e Agrotecnologia)

ABSTRACT

Precompression stress is an important property for assessment of tropical soil structure sustainability and is often determined in laboratory tests. The objective of this study was to compare the load bearing capacity models obtained with controlled moisture in laboratory and those obtained with natural field moistures determined a long one year. The evaluation of soil structural sustainability follows four distinct steps: soil sampling in the field, uniaxial compression test of the samples in the laboratory, determination of precompression stress and estimation of the load bearing capacity models. Laboratory estimates of precompression stress were obtained from moisture controlled in laboratory and from natural moisture determined in a field a long one year. In this process, the soil samples were saturated by capillarity with distilled water in laboratory, and after 48 hours, the samples were air dried to obtain the different moisture contents. Then, the precompression stress was determined for this both conditions. To verify if the load bearing capacity models obtained with controlled moisture in laboratory may represent the load bearing models obtained with natural field moisture, these models were compared using the homogeneity test procedure. It was observed that 75% of field models analyzed were similar to the laboratory models. Thus, due to the similarity on the load-bearing capacity models obtained using natural (field) or controlled (laboratory) moisture contents, the assessment of the soil structure sustainability can be done using both methods.

Index terms: agricultural traffic, *Coffea Arabica L.*, homogeneity test, precompression stress.

RESUMO

Pressão de pré-consolidação é uma importante propriedade na avaliação da sustentabilidade estrutural do solo e é determinada em testes de laboratório. O objetivo deste estudo foi comparar modelos de capacidade de suporte de carga obtidos com umidade controlada em laboratório e obtidos com umidade natural de campo obtido ao longo de um ano. A avaliação da sustentabilidade estrutural do solo ocorreu em quatro etapas: coleta de amostras de solo indeformado, ensaio de compressão uniaxial das amostras em laboratório, estimativa da pressão de pré-consolidação e obtenção dos modelos de capacidade de suporte de carga. As estimativas da pressão de pré-consolidação em laboratório foram obtidas com umidades controladas em laboratório e a de umidade natural foram obtidas com umidade de campo ao longo de um ano. No laboratório, as amostras de solo foram saturadas por capilaridade, com água destilada e depois de 48 horas, foram secas ao ar para obter diferentes valores de umidade. Em seguida, realizou-se o ensaio de compressão uniaxial das amostras e a pressão de pré-consolidação foi determinada para as duas condições aqui proposta. Para verificar se os modelos de capacidade de suporte de carga obtidos com umidade controlada em laboratório podem representar os modelos de capacidade de suporte de carga obtidos com umidade natural, estes modelos foram comparados utilizando o teste de homogeneidade de dados. Observou-se que 75% dos modelos com umidade de campo foram semelhantes aos modelos obtidos com umidade controlada em laboratório. Portanto, devido a similaridade, a análise da sustentabilidade estrutural do solo pode ser feita por ambos modelos de

capacidade de suporte carga, ou seja, obtidos com amostras de solo com umidade natural (campo) ou com umidade controlada (laboratório).

Termos para indexação: *Coffea Arabica L.*, teste de homogeneidade, pressão de pré-consolidação, tráfego agrícola.

INTRODUCTION

When soil is under stress a characteristic relationship between compressive stress and volume change can be used to define some important soil physico-mechanical properties (GREGORY et al., 2006). One of these properties is the precompression stress. The first calculations of precompression stress, a graphical estimation procedure were described by Casagrande (1936). This author defined precompression stress as the maximum past vertical effective stress applied to the soil and correlated it to the change in slope of a curve of void ratio versus logarithm of the vertical effective stress obtained from a one-dimensional consolidation test (LEROUEILL; SAMSON; BOZOZUK, 1983). This approximation represents an elasto-plastic model (KELLER et al., 2011), with the precompression stress representing the transition point between the secondary compression curve (elastic deformation) and the virgin compression curve (plastic deformation). The secondary compression is generally agreed to reflect the soil management history.

Several methods had been proposed by various researchers in defining the point where the reversible elastic failure becomes irreversible plastic deformation in soil compression curves (CASAGRANDE, 1936; DIAS JUNIOR; PIERCE, 1995; ARVIDSSON; KELLER, 2004; GREGORY et al., 2006). The interest in accurate definition of this point could be related to its wide application in understanding soil structure dynamics. According Dias Junior and Pierce (1995), most of the methods proposed by earlier researchers for the estimation of precompression stress were not easily replicable and some involves subjective judgment. In trying to eliminate the subjective judgment, thereby facilitating accurate estimation, these authors compared five methods with the Casagrande graphical estimation procedure and thereafter developed a spreadsheet procedure for estimating precompression stress for either saturated or unsaturated soil based on data from uniaxial compression tests. The Casagrande method is widely agreed as the standard. Following their work, a number of authors had also evaluated different methods of estimating precompression stress (DIAS JUNIOR; PIERCE, 1995).

The shape of the soil compression curves is largely influenced by the moisture content (DIAS JUNIOR; PIERCE, 1995). Considering this interrelationship in the shape of the soil compression curves and moisture, these authors suggested a soil load bearing capacity (LBC) model based on the soil compression curves, obtained for different moisture conditions. The LBC model may be used to estimate the maximum pressure that can be applied to the soil in order to avoid structural degradation and could also be used to estimate the pressure that roots will need to exert in order to overcome soil strength. This model takes the general form: $\sigma_p=10^{(a+b\theta)}$, were, σ_p is precompression stress (kPa); θ is volumetric soil water content; *a* (linear coefficient or intercept) and *b* (angular coefficient) are empirical parameters for model adjustment.

As one of the most important assessment tools of structure sustainability of the tropical soils, LBC models can be used to compare the effect on soil structure, varying soil managements (DIAS JUNIOR et al., 2005; ARAUJO-JUNIOR et al., 2011; PIRES et al., 2012), different land uses (IORI; DIAS JÚNIOR; SILVA, 2012), and as indicator in evaluating soil vulnerability to compaction (AJAYI et al., 2010), and in the assessment of alleviation of the soil structure in degraded land (DIAS JUNIOR et al., 2007), among others.

In practice the LBC model of soils are obtained from samples with moisture controlled in laboratory by natural drying in the laboratory or varying water tensions. The samples are then used in uniaxial compression test (MARTINS et al., 2012; IORI et al., 2012; PIRES et al., 2012). Hamilton and Crawford (1959) noted that in the laboratory procedure some alterations in results often occur. They noted that stress reduction or changes in principal stress ratio for example, will occur due to soil sampling and specimen preparation and this is probably responsible for most of the disagreement between laboratory results and field observations. In the laboratory the different moisture contents are obtained artificially, whereas models with natural moisture in temporal terms are scanty in the literature. Thus, the objective of this study was to compare the load bearing capacity models obtained with controlled moisture in laboratory and those obtained with natural field moistures determined a long one year.

MATERIAL AND METHODS

The study was conducted in coffee plantations located in the Três Pontas County, South of Minas Gerais State, Brazil (24°26’ S; 47°49’ W, altitude of 905 meters). The region is characterized by predominant relief of undulating topography. The climate according to Koppen is Cwa, that is, altitude tropical, with an average annual temperature of about 18° C. The average annual rainfall is 1,300 mm with the highest concentration in the months from December to February. The soil of the study area was classified as a Red-Yellow Latosol (Oxisol) clayey texture (EMBRAPA, 2006) with 510 g kg^{-1} of clay, 200 g kg^{-1} of sand and 290 g kg^{-1} of silt, and particle density of 2.62 Mg m^{-3}.

According to the area history prior to the installation of the coffee plantations, the soil was plowed and disking to a 40 cm deep and then harrowed. All equipment used in the coffee crop management was pulled by a Massey Ferguson 265 tractor, with a mass of about 3,940 kg. The equipment used during a cropping season are fertilizer miname with approximate mass of 210 kg (3 passes per year), spray jet Arbus 400 Jacto with 400 L capacity and mass of 230 kg (3 passes per year), mower Kamaq with a mass of 340 kg (3 passes per year) and the spray jet PH 400 with 400 L capacity and mass of 210 kg (2 passes per year). Thus the total number of passes of the tractor per year is 11 on the same traffic line for each plot at different establishment times.

Samples were collected in this study in coffee plantations with different establishment times. They are 2 years (planted in 2008 with spacing 3.5 m x 0.7 m – Cultivar Mundo Novo), 7 years (planted in 2003 with spacing 3.5 m x 0.9 m – Cultivate Paraíso MG), 18 years (planted in 1992 with spacing 3.5 m x 1.0 m – Cultivate Mundo Novo) and 33 years (planted in 1977 with spacing 3.5 m x 2.0 m – Cultivate Catuaí Amarelo) of establishment. In these coffee plantations were selected areas (coffee row) with side slope of 3, 9 and 15% (Figure 1). Sample were collected in three positions along the coffee row: bottom of traffic line (B), inter-row (I) and top traffic line (T) (Figure 1) at two depths: 0.00 m – 0.03 m (Topsoil) and 0.15 m – 0.18 m (Sub-surface). In total 72 conditions were collected (4 establishment times x 3 slopes x 3 positions x 2 depths).

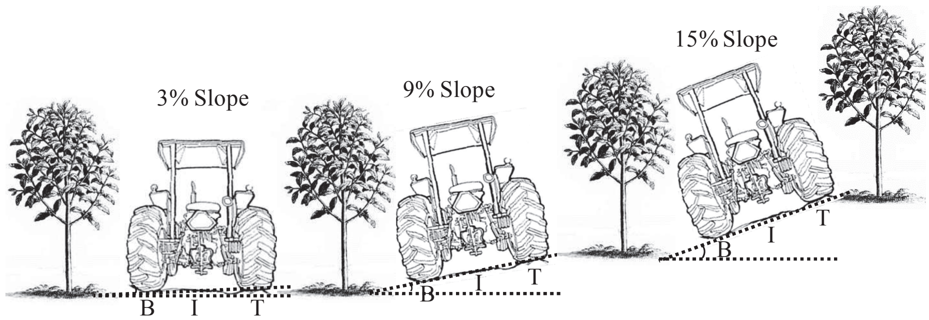

Figure 1 – Schematic representation of the sampling points in the coffee row with three side slope (3, 9 and 15% slope). B: bottom traffic line, I: inter-row and T: top traffic line.

The soil structure sustainability under the presented conditions and management were evaluated in four distinct steps: soil sampling in the field, uniaxial compression test of the samples in the laboratory, estimation of precompression stress to obtain the load bearing capacity (LBC) models. The detail as presented hereafter.

Soil Sampling – Undisturbed soil samples were collected in sampling rings measuring 2.54 cm in height and 6.40 cm diameter, which is compatible with the consolidation rings of the consolidometer. The rings were gently pushed into the soil with Uhland soil sampler. The collected samples are properly wrapped in waterproof-plastic wrap and paraffin wax, to maintain the field moisture content and preserve the structures of the collected samples while being transported to the laboratory.

Uniaxial compression test – In order to procedure the uniaxial compression test in the undisturbed soil samples with controlled moisture content in the laboratory, the samples were saturated with distilled water by capillarity, and after 48 hours, the samples were dried in open air to obtain the different moisture contents. After reaching this desired moisture contents, the samples were used in uniaxial compression test according to the procedure of Bowles (1986) modified by Dias Junior and Pierce (1995). It was used the pneumatic S-450 Terraload floating ring consolidometer (Durham Geo Enterprises, USA) where loads are applied in form of pressure by compressed air. The levels of pressure applied to the soil samples were 25, 50, 100, 200, 400, 800 and 1600 kPa, observing the assumption Taylor (1948), which defines the maximum deflection of up to 90% of the soil sample, for each pressure level.

Precompression stress estimation – plotting the values of deformation in the samples (void ratio or bulk density) against the logarithm of the pressure applied, it was obtained the soil compression curve, from wherein the precompression stress (σ_p) was estimated, observing the assumptions of method

1 or 3, according to Dias Junior and Pierce (1995) which partition the methods depending on the soil moisture tension.

Constructing the load bearing capacity (LBC) models – the precompression stress (σ_p) values was plotted as a function of the volumetric moisture content to which each sample was adjusted in the laboratory and it was fitted the curves with the model proposed by Dias Junior and Pierce (1995):

$$\sigma_p = 10^{(a+b\theta)} \qquad \text{(eq. 1)}$$

Where, σ_p is precompression stress (kPa); θ is volumetric soil water content (m^3 m^{-3}); a (linear coefficient or intercept) and b (angular coefficient) are empirical parameters for model adjustment. For laboratory model, it was used 14 soil samples (n = 14) collected in November 2010 for construction of each model. It was obtained one LBC models for reach 72 conditions considered in this study and the models are hereafter referred to as the "lab model".

For the construction of the field LBC models, "field model", it was followed the four steps earlier enumerated. The only difference was the soil samples were not saturated. The compression test was conducted on the soil at their natural "field" moisture content. However to ensure that the precompression stress are estimated at varying moisture content, it was collected samples round the year (October/2010 to September/2011), since the region had varying soil moisture status at different months reflective of the rainfall; distribution pattern (Figure 2). It was determined the precompression stress of 12 soil samples (n = 12, i.e. one sample per month) for the "field model" and also constructed one load bearing capacity model for reach 72 conditions in this study. Thus, in this study were used 1,872 total soil samples (12 soil samples for each "field model" and 14 soil samples for each "lab model" in 72 conditions).

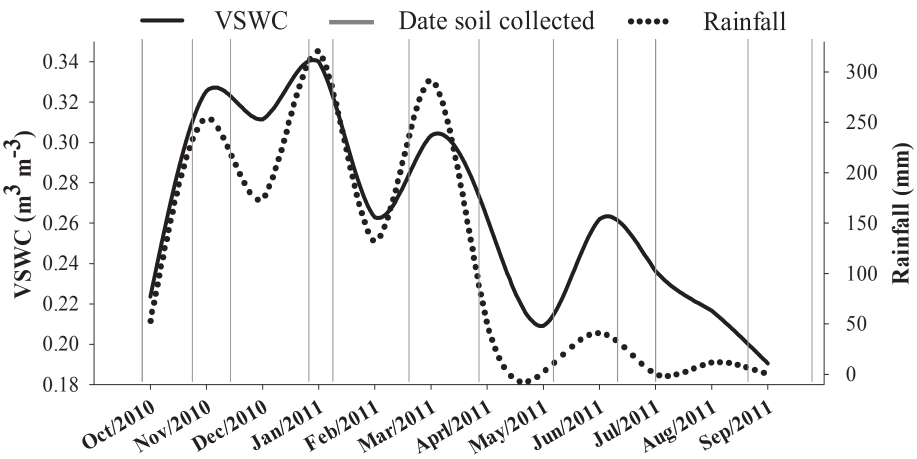

Figure 2 – Volumetric soil water content (VSWC) for different dates, rainfall data for study area and dates of each soil collect realized in 2010 and 2011.

After obtaining the soil LBC models for both laboratory and field conditions, it was compared all the "lab" models with the "field" models. The models were compared using the homogeneity test procedure of Snedecor and Cochran (1989). The procedure compares two linear models. To obtain linear models from the exponential model used in the construction of the LBC model (eq. 1), the logarithm model was linearized by finding the logarithm of both sides. In the test, the linear coefficient or intercept ("a") and the angular coefficient ("b") of the model equation were compared for homogeneity by *F*-test (ARAUJO-JUNIOR et al., 2011). When two models are homogenous and when there are no significance differences between their coefficients ("a" and "b"), the data can be pulled together and representative single model constructed (SNEDECOR; COCHRAN, 1989).

RESULTS AND DISCUSSION

All LBC models in this work presented significant exponential decay relationship for precompression stress with soil water content as similarly observed in several other studies (DIAS JUNIOR et al. 2005; AJAYI et al. 2010; ARAUJO-JUNIOR et al. 2011; MARTINS et al. 2012; PIRES et al. 2012). Table 1 presents the results of the significance test according to Snedecor and Cochran (1989) for the LBC models for “lab” and “field” soil samples. It was observed that 75% of field models analyzed were similar to lab models. Most of the field and lab models soil samples presented similar structure, resulting in equal LBC. This was similarly observed by Shafiq, Hassan, Ahmad (1994), in a comparison of laboratory and field measurements of some soil physical properties including penetration resistance and bulk density. They however observed that the laboratory measurement overpredicted the compaction compared to the field conditions. For these authors, their observation may be attributed to the differences in arrangement of soil pores under laboratory and field conditions as the soils disturbed and undisturbed respectively in the test. Similarly, Arvidsson (1998) obtained similar result in his work on field and laboratory compression experiments. He noted that compression was greater in the laboratory than in the field, and submitted that the differences may be due to the longer loading time in the uniaxial test machine, differences in settlement and relaxation cycle between soil types and differences in soil strength between the soil in the field and the disturbed soil used in the laboratory test.

Table 1 – Comparison of LBC model [$\sigma_p = 10^{(a+b\theta)}$] obtained from the field and laboratory model following the procedures of Snedecor and Cochran (1989).

S	D	P	Years of establishment for coffee areas											
			2 years			7 years			18 years			33 years		
			Comparison items											
			F	B	a	F	b	a	F	b	a	F	b	A
3	Top	I	H	NS	NS	H	NS	**	H	NS	**	H	NS	NS
		B	H	NS	NS	H	NS	NS	H	NS	NS	H	NS	NS
		T	H	NS	NS	H	NS	NS	H	NS	NS	H	NS	NS
	Sub	I	H	NS	NS	H	NS	**	H	NS	NS	H	**	NS
		B	H	NS	NS	H	NS	**	H	NS	**	H	NS	NS
		T	H	NS	NS	H	NS	NS	H	NS	**	H	NS	NS
9	Top	I	H	NS	**	H	NS	NS	H	NS	NS	H	NS	NS
		B	H	NS	NS	H	NS	**	H	NS	NS	H	NS	NS
		T	H	NS	NS	H	NS	NS	H	NS	NS	H	NS	NS
	Sub	I	H	NS	NS	H	NS	NS	H	NS	NS	H	NS	NS
		B	H	NS	NS	H	NS	NS	H	NS	NS	H	NS	**
		T	H	NS	NS	H	NS	**	H	NS	**	H	NS	NS
15	Top	I	H	NS	NS	H	NS	**	H	NS	**	H	NS	**
		B	H	NS	NS	H	NS	NS	H	NS	NS	H	NS	NS
		T	H	NS	NS	H	NS	NS	H	NS	NS	H	NS	NS
	Sub	I	H	NS	NS	H	NS	**	H	NS	NS	H	NS	NS
		B	H	NS	NS	H	NS	NS	H	NS	**	H	NS	NS
		T	H	NS	NS	H	NS	NS	H	NS	**	H	NS	NS

S: slope (%), D: depth, P: sampling position, Top: topsoil, Sub: sub-surface, I: inter-row, B: bottom traffic line, T: top traffic line, F: test for homogeneity; b: angular coefficient, a: intercept, H: homogeneous, **: significant ($p<0.01$) e NS: not significant.

The main difference for lab and field models was only between the "a" parameters. The *F*-test for data homogeneity and angular coefficient (b) between these models were not significant. Soil LBC models for lab and field had the same behavior. But, even on cases in that the models (lab and field) were similar, it was observed that the lab models had lower soil load support capacity when compared to the field model, in the other words, there were slight shift of field model in relation to lab model. It was observed that there was a slight upward shift for similar models. On the other hand, it was observed a strong upward shift for different models (lab and field). The upward shift indicates higher LBC and more soil compaction and this upward shift occurred for all models that it was analyzed. The soil sampling for lab models occurred in November/2010 but for field models the soil sampling occurred over a year (Since October/2010 to September/2011). Within the period of sampling collection (November/2010 – for "Lab" samples and Nov. 2010 until September/2011 – for "Field" samples) some field operations (trafficking of machine in the coffee plantations) never stopped. Because of this, there were changes in the structure of the soil and increase in the soil LBC in the coffee planted areas. In spite of these changes, 75% of the LBC, models analyzed were similar (Table 1). Modifications on soil structure due traffic machine in the coffee plantations were also observed by Miranda et al. (2003), Gontijo et al. (2008), Araujo-Junior et al. (2011), Carmo et al. (2011) and Martins et al. (2012).

It was compared the various parameters of the "lab" and "field" models in this study in other to fully understand the causative and magnitude of the differences or similarity. For the angular coefficient ("b" parameter eq. 1), it was observed that only 1.4% of lab and field models analyzed were significantly different. The main differences between the models were obtained when compared the linear coefficient ("a" parameter eq. 1), for this parameter, just 23.6% were significantly different.

The high level of similarity between the "b" parameter (Table 1) that it was found in this study indicates that the parameter is more related to some factor of soil characteristics independent of the management or agricultural traffic. On the other hand, the almost total differences between lab and field models were observed on linear coefficient or intercept ("a" parameter eq. 1). The results also indicate that the continuing machine operations promoted alteration in this parameter on field model in relation to lab model. Therefore, it was can conclude that the "a" parameter is influenced by soil management. According observations of Peng et al. (2004) using an exponential model similar ($Y = a\ e^{bX}$; where, Y: precompression stress (kPa); X: soil water content (%); a and b: empirical parameters) to what it was presented here, the "b" parameter was related to the influences of soil attributes such as soil texture and the ("a") parameter values were higher for soil with higher bulk density indicating management influences on soil structure. Similarly the study by Araujo-Junior et al. (2011) related "a" coefficient to the packing state of the solid soil particles.

It was observed 94.4% of similarities between models for coffee plantation aged 2 years. For coffee plantation aged 33 years 83.3% of the models were similar. The highest differences between models were observed in coffee plantation aged 7 and 18 years. For these 61.1% models were similar. The higher percentage value of similarities between models was observed for coffee with 2 and 33 years of establishment, meaning the youngest and the oldest cultivated areas. The high similarity between models of coffee plantation aged 2 and 33 years results probably from the homogeneous soil condition for laboratory and field models. The soil compaction in these areas promoted a homogeneous soil condition between models, thus the difference between the models is not expressed in these compacted soils. Coffee plantation with 2 years of establishment presented higher soil compaction susceptibility due to soil tillage before of the coffee plantation establishment. Thus, the machine traffic in this soil susceptible promoted a soil compaction, resulting in similar soil structure between laboratory and field models. For coffee plantation aged 33 years, the similarity of the models observed also occurred due to equilibrium or stability conditions of these areas, because soil compaction. But, in this older areas (33 years) the soil compaction occurred as result of the accumulate traffic of agricultural machinery over the years.

It was observed also that similarity between models for different side slopes were very close. For the side slope of 3%, 70.8% of the models were similar, for side slope of 9%, 79.2% of the models were similar and for the side slope of 15%, 75% models were similar. When the models were compared for the sampling positions, it was observed that the similarity order was top traffic line > bottom traffic line > inter-rows, with 83.3, 79.2 and 62.5%, respectively. These results suggest that the more impact on soil structure happened in traffic lines, causing higher LBC than lines without traffic (inter-rows). Because of this, more difference between lab and field models was observed than on the inter-rows. Inter-rows have a structural condition that is more preserved, and any disturbance will cause notable structure alteration. Working on various sampling positions including traffic line and inter-rows, Miranda et al. (2003) and Gontijo et al. (2008) found a lower LBC on the inter-rows than on traffic lines.

At the topsoil 80.6% of the lab and field models were similar while in the sub-surface 69.4% of the models were similar. The biggest similarity between the models in the topsoil than sub-surface can be due to greater homogeneity of soil tillage in this layer. At greater depths, soil tillage may not have been as homogeneous as it was on the topsoil, may have provided variability in soil structure, resulting in these differences between laboratory models and field.

CONCLUSIONS

Due to the similarity on the load-bearing capacity models obtained using natural (field) or controlled (laboratory) moisture contents, the assessment of the soil structure sustainability can be done using both methods.

ACKNOWLEDGEMENTS

We sincerely appreciate the “Consórcio Brasileiro de Pesquisa e Desenvolvimento do Café CBP&D/Café” and CAPES, FAPEMIG and CNPq for financial support for the research.

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ARTIGO 3: SEASONAL CHANGE OF SOIL PRECOMPRESSION STRESS IN A COFFEE PLANTATION UNDER SUB-HUMID TROPICAL CONDITION

(Preparado de acordo com as normas da Revista Coffee Science)

ABSTRACT: The objective of this study was to describe the seasonal change of precompression stress behavior in coffee plantations in the sub-humid tropic zone of Brazil as affected by agriculture traffic associated to the time since the establishment the coffee plantation, field slope, sampling position in inter-row of the coffee plantation and two layers. The coffee plantation have a uniform soil type; Red-Yellow Latosol and were aged 2, 7, 18 and 33 years. Areas with side slope of 3, 9 and 15% were selected in these coffee plantations. The soil was sampled at three positions on the coffee plantation row (bottom of traffic line, inter-row and top of traffic line) and at two layers (topsoil and sub-surface). It was collected soil samples during one year for each month of year. The study showed that the time since the establishment of a coffee farm and the slope steepness had significant effect on soil disturbance in mechanized operation, with areas that the coffee plants with longer establishment time and with more terrain side slope had higher precompression stress. Top traffic line presented higher load-bearing capacity than inter-row and bottom traffic line. The period from November to January is the period that the soil is more susceptible to compaction, because the Red-Yellow Latosol presented lower load-bearing capacity than the stress applied by tractor used in coffee management practices.

Key words: agricultural traffic; *Coffea Arabica L.*; load-bearing capacity; soil degradation.

SEASONAL CHANGE OF SOIL PRECOMPRESSION STRESS IN A COFFEE PLANTATION UNDER SUB-HUMID TROPICAL CONDITION

RESUMO: Este trabalho teve como objetivo avaliar o comportamento da pressão de pré-consolidação no decorrer de um ano em um Latossolo Vermelho-Amarelo cultivado com cafeeiros de diferentes tempos de implantação em diversas declividades do terreno. Este estudo foi conduzido em plantações cafeeiras localizadas em Três Pontas, sul de Minas Gerais. O solo da área de estudo foi classificado como Latossolo Vermelho-Amarelo. O trator utilizado na área de estudo foi um Massey Ferguson 265. Este estudo foi conduzido em plantações cafeeiras com 2, 7, 18 e 33 anos de implantação. Nestas plantações foram selecionados ruas de café com 3, 9 e 15% de declividade. Foram coletadas amostras de solo indeformadas e deformadas na linha de tráfego de cima e de baixo e na entrelinha do cafeeiro, nas camadas de 0,0 a 0,03 m e 0,15 a 0,18 m. A avaliação da pressão de pré-consolidação ao longo de um ano indicou que o tempo de cultivo e a declividade do terreno tiveram um efeito significativo sobre a alteração estrutural do solo, sendo as áreas com maior tempo de cultivo e as mais declivosas que apresentaram os maiores valores de pressão de pré-consolidação. A linha de tráfego de cima apresentou maior capacidade de suporte de carga do que a entrelinha e a linha de tráfego de baixo. O período de novembro a janeiro foi a época mais crítica para o tráfego agrícola, devido o Latossolo Vermelho-Amarelo apresentar baixa capacidade de suporte de carga e ser este o período crítico em termos de umidade no solo.

Palavras-chave: capacidade de suporte de carga; *Coffea Arabica L.*; degradação do solo; tráfego agrícola.

1 INTRODUCTION

Soil compaction has long been recognized as one of factors affecting crop production (GUIMARÃES; STONE; MOREIRA, 2002; MEROTTO; MUNDSTOCK, 1999; TORMENA et al., 1998; VIEIRA; MUZILLI, 1984). The precompression stress, measured by uniaxial compression tests (ARAUJO-JUNIOR; DIAS JUNIOR; GUIMARÃES, 2008; DIAS JUNIOR, 1994; PAIS et al., 2011; SILVA et al., 2003a; SILVA et al., 2009), is a useful physical-mechanical value that may be used as a reference to describe the maximum load-bearing capacity (DIAS JUNIOR; PIERCE, 1995; SEVERIANO et al., 2009; SILVA et al., 2003b). Besides, precompression stress has also been used as a measure of soil compaction susceptibility (AJAYI et al., 2010; ARAUJO-JUNIOR et al., 2011; IORI et al., 2012), thereby, loads that exceed the precompression stress value leads to additional soil compaction (DIAS JUNIOR, 1994).

Soil water content has a fundamental role in precompression stress. Dias Junior (1994) highlights that for the same condition; soil water content is the factor that governs the amount of deformation that may occur in the soil. Similarly Hillel (1980) submits that soil moisture is the most important soil physical properties that influence soil - machine interactions. Thus, load applied by agricultural machine and equipment and the soil water content is the most important factors to be considered to avoid critical soil compaction.

In spite of its importance to sustainable mechanized agricultural production there are only few studies in Brazil that quantify the pressure levels that can be applied to avoid critical soil compaction (OLIVEIRA et al., 2003; SEVERIANO et al., 2011). Araujo-Junior et al. (2011) studying the impact of different agricultural management practices on soil structural sustainability found a critical water content for the traffic of machines and equipment on a Latossol. These authors considered only those stress that can cause additional soil compaction or change the initial state of the soil structure, and these are considered as stress that do not exceed internal strength of the soil as expressed by precompression stress.

Therefore, studies that identify and establish the adequate soil moisture conditions for the traffic of agricultural machinery and the pressure applied to the soil that would exceed their load-bearing capacity are important to avoid soil compaction. In order to minimize or avoid further compaction caused to soil during agricultural operations, it is desirable also to find seasons or periods of the year during which the soil is more vulnerable to the soil compaction. Silva et al. (2006) found out that changes in precompression stress due to mechanized operations in the rainy season are greater than those observed in the dry season, indicating a lowering of the load-bearing capacity of the soil with increasing soil water content. In many part of Brazil, there are well-defined rainy season and dry season, with 88% of the rain occurring mostly between the months of November to March.

Due to the reduction of precompression stress in the rainy season compared to the dry season, it is very important to control the traffic of agricultural machine at these periods. Previous studies have shown that repeated traffic of agricultural equipment increases the degradation of soil structure (DIAS JUNIOR et al., 2008; SILVA et al., 2007; SILVA et al., 2011). Martins et al. (2012) studying soil degradation in coffee plantations with 2, 7, 18 and 33 years of establishment, observed that the percentage of compacted soil samples increases with the establishment time, indicating that older plantation had accumulated relatively more traffic. Najafi, Solgi and Sadeghi (2009, 2010) also found increase soil disturbance with increases of traffic intensity. Besides traffic intensity, these authors observed that the slope steepness had a significant effect on soil disturbance, with the soil disturbance higher in the steepy terrain conditions.

Seasonal change of the soil precompression stress in coffee growing areas of Brazil are limited and information in the literature on seasonal trend of precompression stress of agricultural soils is scarce. Thus, to establish the impact of mechanized operation in coffee culture, it is essential to identify the factors which affect and alter the soil structure. The development and implementation of practical guidelines in order to manage soil compaction for a wide range of conditions depend upon an understanding of the relative importance of applied pressure and water content during the compaction process (SMITH et al., 1997). The aim of this study was to describe the seasonal change of soil precompression stress behavior in coffee plantations in the sub-humid tropic zone of Brazil as affected by agriculture traffic associated to the time since the establishment the coffee plantation, the filed slope and in three sampling position in inter-row of the coffee plantation.

2 MATERIAL AND METHODS

The study was conducted in coffee plantations located in Três Pontas County, South of Minas Gerais State, Brazil (24°26’ S; 47°49’ W’ and altitude of 905m). This region presents predominant relief of undulating topography. The climate according to Koppen is Cwa, that is, altitude tropical, with an average annual temperature of about 18° C. The annual rainfall measured during the study was 1330 mm (Figure 1). In South of Minas Gerais State a year is characterized with some distinct climatic conditions, with two major seasons per year; rainy season from November to April, and dry season from May to October. The soil of the study area was classified as a clayey textured Red-Yellow Latosol (Oxisol) (Empresa Brasileira de Pesquisas Agropecuária – EMBRAPA, 2006) with 510 g kg^{-1} of clay, 200 g kg^{-1} of sand and 290 g kg^{-1} of silt, and particle density of 2.62 g cm^{-3}. It was collected soil samples over one year (October 2010 to September 2011) once every month on the date, indicated in Figure 1.

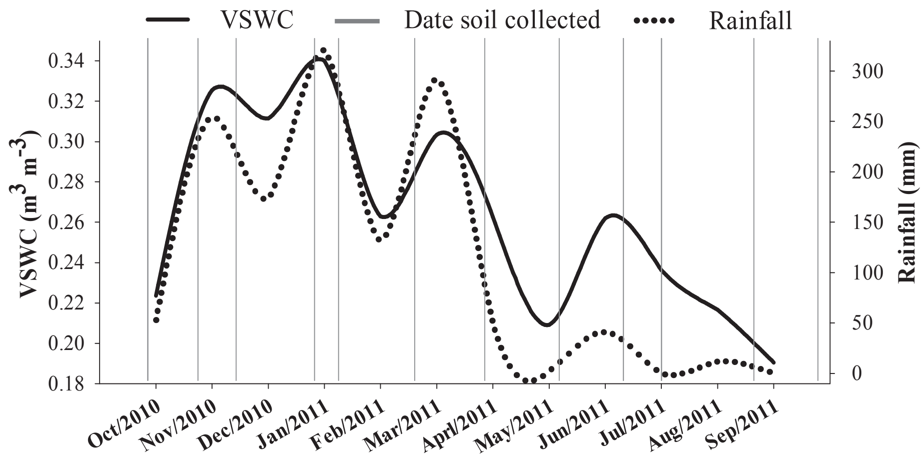

FIGURE 1 – Volumetric soil water content (VSWC) for different dates, rainfall data for study area and dates of each soil collect (represented by vertical lines) realized in 2010 and 2011.

According to the farms records, prior to the installation of the coffee plantations, the soil was plowed and disked once to a depth of 40 cm and then harrowed. All the equipment used in the coffee crop management were pulled by a Massey Ferguson 265 tractor, with a mass of about 3,940 kg, front tyre type 6 - 16 (contact area of 381 cm^2) and rear tyre type 16.9 - 24 (contact area of 2145 cm^2). The equipment pulled by the tractor are: fertilizer miname with approximate mass of 210 kg (3 passes per year), spray jet Arbus 400 Jacto with 400 L capacity and mass of 230 kg (3 passes per year), mower Kamaq with a mass of 340 kg (3 passes per year) and the spray jet PH 400 with 400 L capacity and mass of 210 kg (2 passes per year). Thus the total number of passes per year of the tractor is 11 on the same traffic line for each plantation at different ages since establishment.

This study was conducted in coffee plantations with 2 years (planted in 2008 with spacing 3.5 m x 0.7 m – Cultivate Mundo Novo), 7 years (planted in 2003 with spacing 3.5 m x 0.9 m – Cultivate Paraíso MG), 18 years (planted in 1992 with spacing 3.5 m x 1.0 m – Cultivate Mundo Novo) and 33 years (planted in 1977 with spacing 3.5 m x 2.0 m – Cultivate Catuaí Amarelo) of establishment. In these coffee plantations were selected areas (coffee row) with side slope of 3, 9 and 15%. The soil were sampled at three positions on the coffee row (Figure 2): bottom of traffic line (B), inter-row (I) and top of traffic line (T) at two layers: 0.00 m – 0.03 m (topsoil) and 0.15 m – 0.18 m (sub-surface). Thus, samples were collected from these seventy two conditions (4 establishment times x 3 slopes x 3 sampling positions x 2 depths).

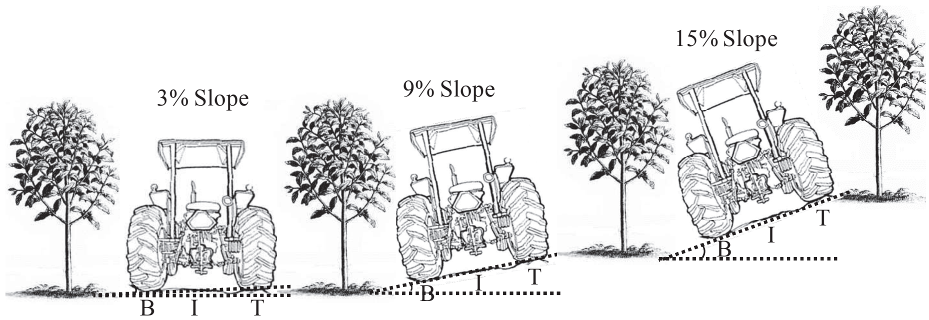

FIGURE 2 – Schematic representation of the sampling points in the coffee row with three side slope (3, 9 and 15% slope). B: bottom traffic line, I: inter-row and T: top traffic line.

The evaluation of the soil precompression stress occurred in four distinct steps. Sampling the soil in the field, uniaxial compression test on the samples in the laboratory, determination of the precompression stress and estimation of the load-bearing capacity models, as detailed follows:

Soil sampling process – Soil samples were collected in sampling rings with dimensions 2.54 x 6.40 cm. The rings was pushed into the soil with Uhland soil sampler, after which the samples was properly waterproofed (wrapped in plastic and paraffin), to maintain the field moisture and preserve the soil structure during transport to the laboratory.

Uniaxial compression test – in the laboratory, it was submitted the samples to uniaxial compression test in a fixed ring consolidometer according to the procedure of Bowles (1986) modified by Dias Junior (1994). It was used pneumatic S-450 Terra load floating ring consolidometer (Durham Geo Enterprises, USA) where pressures are applied from compressed air. The levels of pressure applied to the soil samples were 25; 50; 100; 200; 400; 800 and 1,600 kPa, following the assumption of Taylor (1948), which defines the maximum deflection up to 90% of the soil sample, for each pressure step. The uniaxial compression tests were realized with soil samples at the field moisture content. Thus, the soil water content was determined by oven drying at 105-110°C for 48 hours after this test.

Determination of precompression stress – Using the values of sample deformation (bulk density) against the logarithm of the pressure applied, it was obtained the soil compression curve from which the precompression stress (σ_p) was estimated for each sample (DIAS JUNIOR; PIERCE, 1995).

3 RESULTS AND DISCUSSION

Figure 3 presents the changes in the precompression stress (σ_p) and volumetric soil water content for the coffee plantation with ages 2, 7, 18 and 33 years of establishment for the period October/2010 to September/2011. The plantation with 33 years of establishment always presented lower volumetric soil water content than other areas during the study period. And, the largest difference for soil water content, between old area (33 years of establishment) than younger areas (2, 7 and 18 years of establishment), were observed in wet periods. Thus, this low volumetric soil water content at areas with 33 years of establishment caused higher precompression stress values than others areas (2, 7 and 18 years of establishment). Iori et al. (2012) simulating two soil moisture behaviors (wetter and drier seasons) in load-bearing capacity also found high values to precompression stress for low soil water contents. These authors indicate that for low soil moisture the soil adhesion is minimal, being the favored cohesion, resulting in higher load-bearing capacity.

The low soil water content observed in the older areas can result greater problems with hydric availability for coffee plants. This low soil water content observed in area with 33 years of establishment, mainly in December/2010, January/2011 and March/2011, can be result of problems with soil water infiltration or soil water retention.

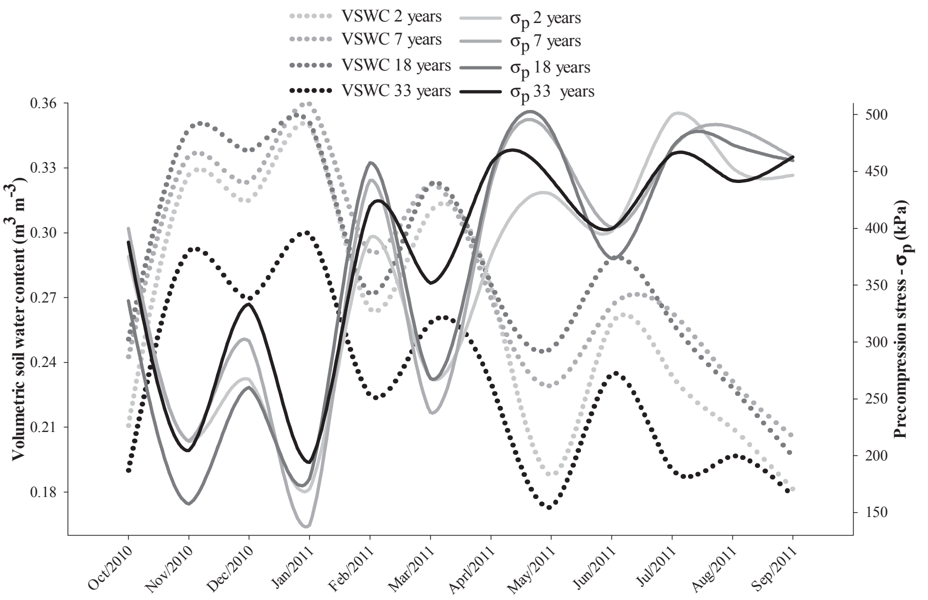

FIGURE 3 – Volumetric soil water content (VSWC) and precompression stress (σ_p) for total period studied for areas of 2, 7, 18 and 33 years of establishment.

The lower precompression stress values indicate lower soil load-bearing capacity and more susceptible to compaction (ARAUJO-JUNIOR et al., 2011;

MARTINS et al., 2012; SANTOS et al., 2009). Thus, areas with 2 years of establishment presented lower load-bearing capacity, consequently, higher susceptible to compaction. Lower precompression stress values in younger coffee plantation were also found by Miranda et al. (2003). Assessing different management systems in coffee areas in Red Latosol, these authors found lower load-bearing capacity in younger areas than older areas when the evaluation was on traffic line. Similarly, Martins et al. (2012) observed for the 0-3 cm layer of the coffee with 7, 18 and 33 years of establishment had higher load-bearing capacity than the 0-3 cm layer for the coffee with 2 years of establishment, but this observation was for volumetric water content lower than 0.18 m^3 m^{-3}. For volumetric soil water content higher than 0.18 m^3 m^{-3} the 0-3 cm layer, these authors found greater load-bearing capacity of the coffee plantation with 2 years of establishment than the other coffee plantations with 7, 18 and 33 years of establishment. In this study, when volumetric soil water content was of 0.21 m3 m-3, on months of June and July/2011, it was observed greater load-bearing capacity in coffee plantation with 2 years of establishment than the others years of establishment.

Figure 4 presents the changes in the precompression stress (sp) and volumetric soil water content for areas inside coffee plantation with side slope of 3, 9 and 15%. Areas with side slope of 3% presented higher volumetric soil water content in dry period (from May to September) than side slope of 9% and 15%. In wet period it was observed similar volumetric soil water content between side slopes, just in November/2010 areas with side slope of 15% presented higher volumetric soil water content than areas with side slope of 3 and 9%. For mechanical behavior of the soil, it was observed that the areas with side slope of 15% presented higher precompression stress values and bigger load-bearing capacity than side slope of 3 and 9%, just in dry period (from May to August). This higher load-bearing capacity in the moderate side slope (side slope of 15%) can indicate a greater resistance to compaction, however, this also imply a higher resistance to the coffee roots penetration (ARAUJO-JUNIOR et al., 2011; MARTINS et al., 2012; MIRANDA et al., 2003) and it is possible indicative that the traffic in steepness areas had more impact on soil structure than in the other side slopes (Figure 4).

Evaluating the operational performance of a tractor running perpendicular to the slope, Leite et al. (2011) found that the slippage of the tires increased with increasing the side slope of the track. These authors showed that there was a significant decrease in the tractive force as the inclinations increased, which can be attributed to a lateral weight transfer also increasing the slippage of the tires. Therefore, slippage of a tractor in side slope can cause high impact on soil structure. Najafi, Solgi and Sadeghi (2009) explain that during skidding on the steepy terrain, a given load gets uneven weight balance on the axles and increases soil disturbance. Jamshidi et al. (2008) also indicate that the uneven load distribution between tires in sloping land can result in higher dynamic peak loads being exerted on the soil. Similarly, Krag, Higgingbotham and Rothwell (1986) also found that slope steepness had a stronger effect on soil disturbance. They observed that during timber harvesting, the soil disturbance was more pronounced on slopes >20% than on slopes <20%. Najafi, Solgi and Sadeghi (2010), studying the effects of skid trail slope and ground skidding on soil disturbance, showed that the soil disturbance increased dramatically on the treatments with the slopes of >20%. Davies, Finey and Richardson (1973) and Raghavan, Mckyes and Beaulieu (1977) also identified wheel slip on agricultural tractors as causing significant compaction.

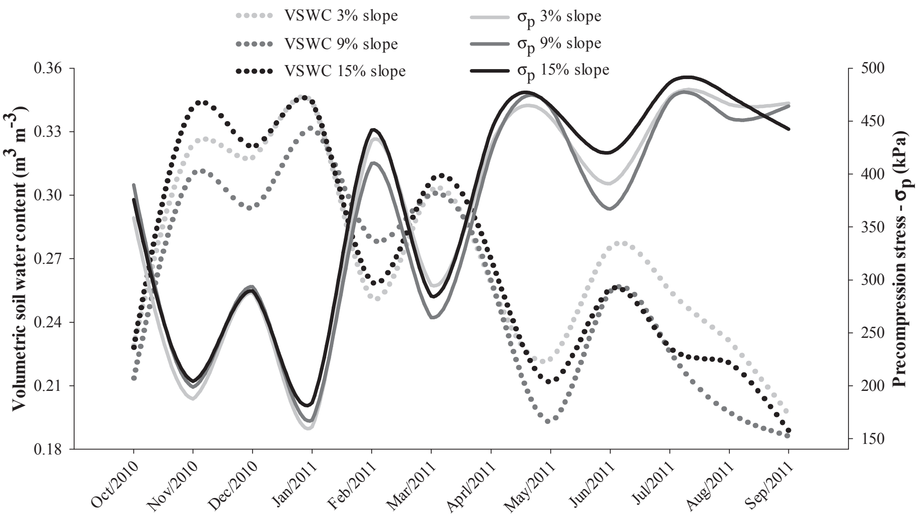

FIGURE 4 – Volumetric soil water content (VSWC) and precompression stress (σ_p) for total period studied for areas with side slope of 3, 9 and 15%.

This study showed that traffic operations in areas with side slope caused impact on soil structure, increasing soil resistance to compaction, but, besides soil disturbance, a steep terrain may cause instability of the tractor. In his work, Pota, Katupitiya and Eaton (2007) showed the importance of the optimal operational slope for the stability of tractors and safety of agricultural operations.

The observed precompression stresses and volumetric soil water content for the bottom traffic line, inter-row and top traffic line are presented in figure 5. It was observed higher volumetric soil water content for bottom traffic line in period from November/2010 to February/2011. The other sampling positions (inter-row and top traffic line) had similar volumetric soil water content for this period (November/2010 to February/2011). The bottom traffic line is the place that stays in inferior part on side slope, as was observed in the figure 2, thus the water accumulated in this place is biggest than other sampling positions. For other hand, in the period from May/2011 to September/2011 (dry period), it was observed low volumetric soil water content in the top traffic line. The inter-row presented similar volumetric soil water content with top traffic line in the period from October to February. Already in the period from May to September, the similarity for volumetric soil water content was observed between inter-row and bottom traffic line. Just on the period from March to April, inter-row presented lower volumetric soil water content than traffic lines. But in this period, it was observed higher load-bearing capacity for bottom traffic line. However, in general, the low load-bearing capacity was observed for inter-row and bottom traffic line, because in 60% of period studied, it was observed that top traffic line had higher load-bearing capacity. Leite et al. (2011) found that top traffic line had more slippage than bottom traffic line in side slope, being that this difference of slippage, between side tires, increased with increase the side slope. Khoury Junior et al. (2009) noted that this happens, because the shift of the lateral weight to the lower end of the slope, causing loss the tire ground contact. The loss tire ground contact causes slippage resulting in more soil disturbance.

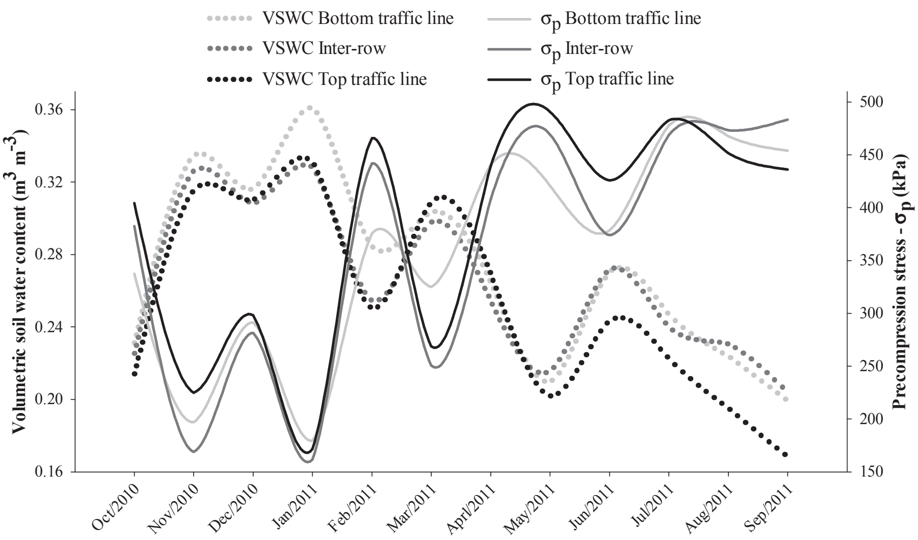

FIGURE 5 – Volumetric soil water content (VSWC) and precompression stress (σ_p) for total period studied for bottom traffic line, inter-row and top traffic line positions.

The lower precompression stress find at bottom traffic line indicate higher susceptibility of soil to compaction, being this traffic line the one with more possibility have problems with soil compaction. This problem with soil compaction was observed by Martins et al. (2012), who found the compaction that occurred on the traffic line located at the bottom of the ground was equal or greater than the compaction that occurred in the traffic line located at the top of the ground.

It was evaluated load-bearing capacity and volumetric soil water for two soil layers in this study (Figure 6). On months from October to December, the topsoil (0.00-0.03 m) presented higher volumetric soil water content than sub-surface (0.15-0.18 m). Even with higher soil water content, the topsoil presented higher precompression stress values than sub-surface, for this same period. Wet soils have more susceptibility to compaction than dry soils. Thus, when the topsoil was more susceptible to compaction than sub-surface, due higher volumetric soil water content, and_the machine traffic occurred in these coffee plantation areas, the soil structure from topsoil was more affected than soil structure from sub-surface, increasing the precompression stress values. Besides, the pressure applied by coffee machine is higher in the topsoil, causing more soil disturbance, what also contributed for the increase the precompression stress values. On the other hand, in dry periods (from April to September) the layer that was more susceptible to compaction was the topsoil, because presented lower precompression stress values. This behavior was not observed due to soil water content, because both layers presented similar volumetric soil water content values. Probably in the sub-surface soil the cohesion between soil particles was bigger than topsoil, resulting in higher load-bearing capacity for sub-surface. In general the organic matter is higher in topsoil than sub-surface and, according to Ferreira et al. (1999), the soil organic matter may disrupt the soil particles, which might have caused this low cohesion in topsoil. This behavior (sub-surface with higher load-bearing capacity than topsoil) wasn't observed in wet periods, because in this period the soil cohesion didn't happen or was minimal, due the higher soil water content.

Analyzing the period from January to April, it was observed that both layers presented similar precompression stress values. These results also were obtained by Martins et al. (2012) who found similarity between layers (0.00-0.03 m and 0.15-0.18 m) in older coffee plantation and explain that this occurs due to the natural structure recovery of the 0.15-0.18 m layer in relation to the 0.00-0.03 m layer.

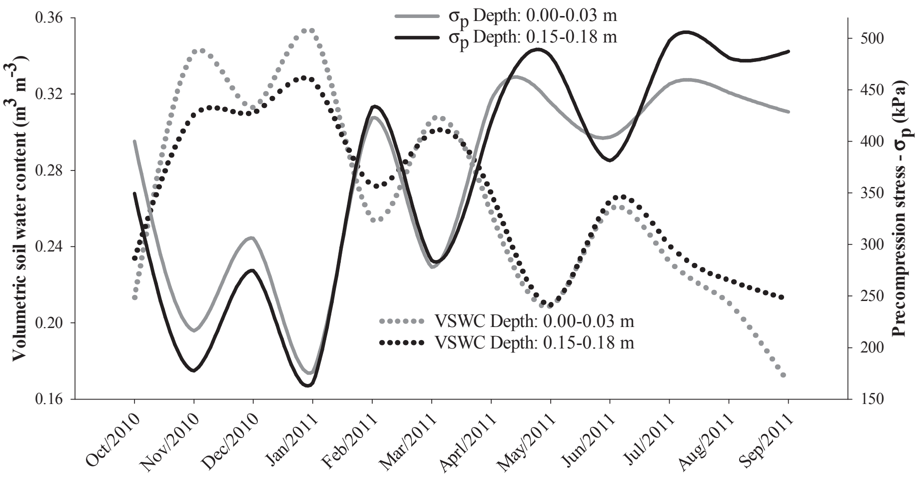

FIGURE 6 – Volumetric soil water content (VSWC) and precompression stress (σ_p) for total period studied for topsoil (0.00-0.03 m) and sub-surface (0.15-0.18 m).

In this study, it was observed the lower precompression stress values occurred in rainy seasons. Silva et al. (2006) also found lower precompression stress values in rainy seasons compared to the dry seasons, and explained that in rainy seasons there is a alleviating of the load-bearing capacity. Therefore, higher impacts on soil structure due coffee machine operations will occur during the rainy season.

4 CONCLUSIONS

The study showed that the time since the establishment of a coffee farm and the slope steepness had significant effect on soil disturbance in mechanized operation, with areas that the coffee plants with longer establishment time and with more terrain lateral inclination had higher precompression stress. Top traffic line presented higher load-bearing capacity than inter-row and bottom traffic line. The period from November to January is the period that the soil is more susceptible to compaction, because the Red-Yellow Latosol presented lower load-bearing capacity than the stress applied by tractor used in coffee management practices.

5 ACKNOWLEDGEMENTS

We sincerely appreciate the "Consórcio Brasileiro de Pesquisa e Desenvolvimento do Café CBP&D/Café" and CAPES, FAPEMIG and CNPq for financial support for the research.

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