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Interrelationships Among Weed Management in Coffee Plantation and Soil Physical Quality

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1. Introducion

Coffee bean is one of the most important commodities produced in Brazil. Brazil is responsible for the supply of about 30% of world coffee bean market. Coffee related enterprises are a major economic driver in the regions where it is cultivated in Brazil and elsewhere as it generates jobs, provide income and stimulate development. However, for greater coffee agribusiness competitiveness , it is necessary to meet social-environmental requirements expected by international consumers (Araujo-Junior et al., 2008).

Among several social-environmental expectations met by coffee farmers internationally, biodiversity conservation, sustainable management and subsequent improvement or maintenance of soil structure in order to avoid or minimize additional soil compaction resulting from inadequate management are vital (Brazil Specialty Coffee Association [BSCA], 2005). These requirements help the coffee farmers develop eco-friendly production practices/guidelines: environmentally appropriate, economically viable, socially beneficial and culturally acceptable in their production system. These production guidelines, help in balancing environmental and socio-economic factors in coffee bean production.

Amongst all agronomic practices involved in coffee production, the weed management strategy/system is one of the most intensive in coffee bean production and critical to eco-friendly management ranging from two to five operations per year. The adopted weed management system in coffee plantations can have major effects on the soil environment,

affecting physical, chemical and biological conditions, resulting in changes soil compressive behavior and load bearing capacity affecting yield potential in coffee plantations (Araujo-Junior et al., 2008; 2011).

Appropriate weed management systems utilized between coffee rows would help in minimizing soil degradation by erosion (Carvalho et al., 2007), reducing compaction and improving soil workability and machines trafficability (Araujo-Junior et al., 2008, 2011). Weed plants utilized as cover crops residues can be left on the soil surface similar to a cereal stubble mulch to protect against evaporations and erosion (Hillel, 1980; Faria et al., 1998). In a newly developed orchard, Yang et al. (2007) observed that the application of herbicides and tillage favored soil erosion. Yang et al. (2007) pointed out that chemical and mechanical methods are the dominant weed control practices in many production systems due to its effectiveness, but noted on the other hand, that weed presence during the rainy season prevented soil erosion. Studies conducted in tropical conditions showed that mechanical and chemical methods for weed control on coffee plantations had a great influence on the soil compaction state (Kurachi & Silveira, 1984; Alcântara & Ferreira, 2000b; Araujo-Junior et al., 2008, 2011), soil surface crust formation, erosion and coffee yield (Silveira et al., 1985; Alcântara & Ferreira, 2000a).

Soil compaction processes are one of the most important causes of soil degradation and changes on soil structure, affecting soil physical quality. Compaction is a reduction of the volume of a given mass of soil and ceases when the soil structure has become strong enough to withstand the applied stress without further failure, in compacted soils volume of pores is reduced (Dexter, 2004). Soil structure is defined as the arrangement of the solid particles and of the pore space located between them (Marshall, 1962). Also, soil structure may be defined as the combination or arrangement of primary soil particles into secondary units or peds. The secondary units are characterized on the basis of size, shape and grade (Soil Science Society American – SSSA, 2008). Structural changes to the soil could alter their physical quality, thereby altering the soil workability and trafficability, infiltrate rate, drainage, water redistribution and water retention, as a function of pore-size distribution. Due to effects of soil residue coverage on soil, the weed management system has direct influence on soil structure management and physical quality and must therefore be considered from both agronomic and environmental viewpoints.

Structural changes resulting from the traditional bare ground weed management system stand out among the main adverse effects of this practice (Kurachi & Silveira, 1984; Silveira & Kurachi, 1985; Faria et al., 1998; Alcântara & Ferreira, 2000a; Araujo-Junior et al., 2008, 2011). Structural changes due to improper soil management make coffee plants more susceptible to dry conditions by the reduction of infiltration rate and gas flow into the soil profile. Inadequate soil aeration and nutritional deficiency, decreases root growth and enhancing soil erosion, resulting in a compromise of the soil and environmental quality in agro-forestry production (Horn, 1988; Dias Junior et al., 2005; Vogeler et al., 2006).

The water content in the soil profile determines the reaction to tillage, and among the physical properties, soil moisture is the most important for soil-machine interactions, since it controls the consistency of the soil (Hillel, 1980) and governs the amount of soil deformation

when subjected to external pressure (Dias Junior & Pierce, 1996). Thus, soil water acts as a lubricant and as a binder between the soils particles, affecting the structural stability and strength of geological materials and soil (Topp & Ferré, 2002).Therefore, knowledge of the interrelationship of weed management and its influence on soil structure is essential to establish sustainable management of the soil in coffee plantations. Mentioned previously, soil structure greatly influences the distribution of the pore size, water and gas movement into the soil, soil strength and soil water retention. Few studies have been investigated the effect of weed management system on soil physical quality. In this book chapter, changes in soil physical attributes (soil bulk density, microporosity, macroporosity, total porosity, soil water retention curve, precompression stress and load bearing capacity) are studied in relation to weed management system in coffee plantation. Load bearing capacity models were developed to assess the influence of the different weed management systems on soil structure.

2. Site description and characterization

The study site was the Experimental Farm of the Minas Gerais State Department for Agriculture and Livestock Research [EPAMIG] (20°55'00'' S, 47°07'10'' W, ≈ 885 m) in the São Sebastião do Paraíso County, State of Minas Gerais, Brazil. The farm has been used for weed control management system experiments since 1977. The average annual temperature of the area is 20.8 °C, (27.6 °C maximum, 14.1 °C, minimum) and the average annual rainfall is 1470 mm (Alcântara & Ferreira, 2000a,b).

The soil in the experimental area is derived from basalt and was classified as a Dystroferric Red Latosol according to the Brazilian Soil Classification System (Brazilian Agricultural Research Council [Embrapa], 2006); Oxisol according to USDA soil taxonomy (Soil Survey Staff, 1998) and Ferralsol (Food and Agriculture Organization [FAO], 2006). Analysis of soil collected close to experimental area under natural forest showed that Dystroferric Red Latosol contains 570 g kg^{-1} clay, 230 g kg^{-1} silt and 200 g kg^{-1} sand, in the top 0 to 30 cm depth and also have a homogeneous structure throughout the profile. The soil has low soil bulk density, high total porosity and macroporosity and exhibit a granular structure like a coffee powder.

2.1 Weed control management systems and conduction of the coffee plantation

Seven weed management systems which had been in use for about 30 years in the coffee plantation were considered in this study (Photo 1; Table 1). The management systems were established in a randomized complete block design with three replicates, each plot 36m in length. The experimental design further included a split-plot with each weed management system in use in three interrows as the main-plot factor, and the soil sampling depths (0–3, 10–13 and 25–28 cm) as a split-plot. In the areas under the coffee canopy, the weeds are managed as needed utilizing manual hoeing or with the application of herbicides. The successful weed management system utilized in the coffee plantation experimental area for the 30 years period prior to treatment establishment influenced the number of operations needed as well as the density and diversity of weeds found in the area at the time of the sampling (Table 1).

Weed management	Operations	Species weed/common name/families
No-Weed Control (NWC)	0	*Marmodica charantia* L., melão-de-são-caetano, Cucurbitaceae; *Ephorbia heterophylla* L., leiteira, Euphorbiaceae; *Digitaria insularis* (L.) Mea ex Ekman, capim-amargoso, Poaceae; *Panicum maximum* Jacq., capim-colonião, Poaceae; *Nicandra physaloides* Gaertn., joá-de-capote, Solanaceae; *Ipomoea acuminata*, corda-de-viola, Convolvulaceae; *Amaranthus viridis,* caruru-de-mancha, Amaranthaceae
Hand Hoeing (HAHO)	8	*Ephorbia heterophylla* L., leiteira, Euphorbiaceae; *Digitaria horizontalis* Willd., capim-colchão, Poaceae; *Cenchrus echinatus* L., timbête, Poaceae.
Rotary Tilling (ROTI)	8	*Cyperus rotundus L,* tiririca, Cyperaceae; *Cynodon dactylon* (L.) Pers., grama-seda, Poaceae; Bidens pilosa L., picão-preto, Compositae.
Post-Emergence Herbicide (POSH)	8	*Amaranthus viridis* (caruru-de-mancha, Amaranthaceae); *Commelina benghalensis* L. (trapoeraba, Commelinaceae).
Mechanical Mowing (MMOW)	9	*Cyperus rotundus L,* tiririca, Cyperaceae; *Cynodon dactylon* (L.) Pers., grama-seda, Poaceae; *Amaranthus viridis,* caruru-de-mancha, Amaranthaceae; *Brachiaria decumbens* Stapf., braquiária, Poaceae.
Disk Harrowing (CTDH)	8	*Cyperus rotundus L,* tiririca, Cyperaceae; *Cynodon dactylon* (L.) Pers., grama-seda, Poaceae; *Brachiaria plantaginea* (Link) Hitchc., marmelada, Poaceae.
Pre-emergence herbicide	6	Without weed plants at the moment of the sampling

Table 1. Weed management system, numbers of operations performed between January 2006 and December 2007, species, common name and genus observed in an experimental area at the time of soil sampling.

1. No-weed control between coffee rows (NWC): the weeds plants were left to grow freely between the coffee rows, thus, high density and diversity of the weed plants were found in the plots at the time of sampling (Table 1).

2. Hand hoeing (HAHO): performed with the aid of a hoe, when the weed reached 45 cm height. These operations were carried out eight times between January 2006 to December 2007 (Table 1).

3. Post-emergence herbicide (POSH): glyphosate, N-(fosfonometil) glicina, was applied with the aid of a knapsack sprayer, at a rate 2.0 L ha-1 of commercial product and 0.72 Kg active ingredient ha-1, soluble concentrate formulation 0,36 Kg L-1, and applied with spray volume of 400 L ha-1, eight applications were performed between January 2006 and December 2007 (Table 1).

4. Mechanical mowing (MMOW): the weed plants were mowed with a mechanical mower Kamaq® model 132 KD, with cutting width of 1.32 m and 340 Kg of static mass

5. Rotary-tilling (ROTI): the axis has five flanges, as two sides with three knives and threes edges with six knives. It's worked at 10 cm depth incorporating the weeds.

6. Coffee tandem disk harrow (CTDH): the equipment is composed by two sections in tandem, each section is equipped with seven flat disks with cut width of 1.3 m and static mass 300 kg. It's worked at 7 cm depth.

7. Pre-emergence herbicide (HPRE): oxyfluorfen (2-cloro-a,a,a-trifluoro-p-tolyl-3-ethoxy-4-nitrophenyl ether), was applied with the aid of a knapsack sprayer, at a rate 2.0 L ha-1 of commercial product and 0.48 Kg active ingredient ha-1 in the soluble concentrate formulation 0.24 Kg L-1, and applied with spray volume of 400 L ha-1 (Rodrigues & Almeida, 2005) six applications were performed from January 2006 to December 2007 (Table 1). For this application, soil surface was free of the vegetation.

A

B

C

Photo 1. Overview of experimental area at the time of the sampling in December 2007. (A) weedy control between coffee rows; (B) pre-emergence herbicide. Note sheet erosion (B) and decreased infiltration due to surface crusting (C) between coffee rows.

The equipment used to apply tillage treatments was mounted on a two-wheel-drive coffee tractor Valmet® model 68. This tractor has engine capacity of 61.9 CV (45 kW), total weight of tractor with equipment was 38.25 kN, front tyres 6-16 (15.24 cm of width x 40.64 cm rim diameter) in inflation pressure 172 kPa and rear tyres 12.4-R28 in inflation pressure 124 kPa. To determine the maximum stress applied by each tyre, the static weight distribution was considered to be 35% for the front tyres and 65% for the rear tyres. The critical volumetric water content for the traffic of the tractor, were considered as those stress that don't exceed the internal strength of the soil expresses in the precompression stress (Araujo-Junior et al., 2011).

2.2 Soil sampling

In each weed management system, 15 undisturbed soil samples (early December, 2007) were collected randomly in the traffic line of the machines and equipments, 80 cm from stems of the coffee trees in the 0–3, 10–13 and 25–28 cm layers, totaling 315 soil samples (15 samples x 3 depths x 7 management system). Additional fifteen samples at each depth were collected in a Dystroferric Red Latosol under natural forest (NAFT) adjacent to coffee cultivation, 45 undisturbed soil samples (15 samples x 3 depths) were collected which served as a reference of soil physical quality. The undisturbed soil samples were collected using a cylindrical Uhland sampler (Uhland, 1949) and aluminum rings, 2.54 cm high by 6.35 cm diameter (Photo 2). The Uhland sampler is pressed into the soil sample in the 0–3 cm depth. To collect the sample at 10–13 cm and 25–28 cm depths, the sampling pit were carefully dug to depths 10 cm and 25 cm.

Photo 2. Uhland undisturbed soil sampler components. 1 – driving assembly; 2 – aluminum cylinder room ; 3- graphite lubricant; 4 – plastic film to cover soil sample; 5 – measuring tape; 6 – mattock for digging soil sampling pit.

2.3 Laboratory analysis

In the laboratory, a knife was used to trim the soil from the ends to the exact size of the rings. This was used to determine the volume of soil and its weight. The scrapped soil materials were later used for physical (particle size distribution, soil particle density) and chemical (total soil organic carbon content) characterization of the soil. The soil particle-size distribution was determined by the pipette method (Day, 1965), by chemical dispersion with a 50 mL 0,1 N sodium hydroxide solution, in contact with the samples for 24 hours. Physical dispersion was accomplished by slowly rotating in a Wiegner mixer that shakes 30 times per minute, adding 20 g coarse sand (Grohmann & Raij, 1977). Soil particle density was determined by the pycnometer method (Blake & Hartge, 1986b). The total soil organic carbon content were determined by wet combustion with carbon oxidation adding 10 mL of digest solution ($Na_2Cr_2O_7$ $2H_2O$ 4 N + H_2SO_4 10 N) (Raij et al., 1987).

Three soil samples for each plot and at the sampled depths were saturated by capillary with distilled water, and equilibrated to a matric potential (Ψm) of - 2 and - 6 kPa, on a suction table (Romano et al., 2002) and - 10, - 33, - 100, - 500 and - 1500 kPa in a ceramic plate inside a pressure chamber (Soilmoisture Equipment Crop., P.O. Box 30025, Santa Barbara, CA 93105) (Dane & Hopmans, 2002). The soil-water retention data were fitted through the van Genuchten (1980) model with Mualen (1976) constraint. The – 6 kPa matric potential was used to separate the pores with effective diameter greater than 50 µm, drained from the cores (macropores). Water retained at this matric potential is considered as a measure of microporosity.

Precompression stresses were determined from the undisturbed soil samples submitted to uniaxial compression tests. The soil samples were kept within the sleeves of the coring cylinder, which were placed in the compression cell, and afterwards subjected pneumatically (Durham Geo Slope Indicator, USA, model S-450 Terraload®) to pressures 25, 50, 100, 200, 400, 800 and 1600 kPa to reach equilibrium (Bowles, 1986). During each test, a normal vertical stress was applied until 90% of the maximum deformation was reached and then the pressure is increased to the next level (Taylor, 1948). After uniaxial compression tests, the undisturbed soil samples were dried in the oven at 105–110 °C for 48 hours to determine the dry soil weight per unit volume, to calculate the soil bulk density (Blake and Hartge, 1986a). The volumetric total porosity (VTP) was estimated using the relationship between bulk density and particle density (Flint & Flint, 2002). Volumetric water content for each sample was also obtained

3. Soil physical properties

3.1 Bulk density and total soil organic carbon

The soils samples from the coffee-cultivated plots subjected to different weed management systems in the traffic line, had a higher bulk density and lower total soil organic carbon at the three layers studied, when compared to the soil samples from natural forest soil (Fig. 1A and 1B). These results indicated that land use with coffee plantation using different mechanical and chemical methods for weed control, increased the packing of the solids particles in soil thereby affecting the soil structural sustainability.

The bulk densities values from soil samples following post-emergence herbicide and mechanical mowing weed management systems at all the depths, and those from the rotary tilling managements (10–13 and 25–28 cm depths), coffee tandem disk harrowing and pre-emergence herbicide (0–3 and 10–13 cm depths) were considered higher than critical values for clay soils (1.2 Mg m^{-3}) in agreement with other studies including Derpsch et al. (1991); Dexter (2004); Severiano et al. (2011) and critical values for coffee root growth in Dystropherric Red Latosol (Araujo-Junior et al., 2011). The disk harrowing and pre-emergence herbicide weed management systems promote the crusting in the soil surface (Photos 1B and 1C) and increase the values of the bulk density (Fig. 1A).

After 30 years of conventional coffee cultivation, the total organic carbon contents were markedly affected by weed control between the coffee rows in the traffic line (Figure 1B). Total organic carbon contents were greater for native forest compared to the coffee plantation at all depths, except at 0–3 cm following mechanical mowing, which had the same total organic carbon (Fig 1A.) this is understandable considering that weed control with mechanical mower cut the weed in all the interrows and concentrate weed near the edge of the equipment increasing the total soil organic carbon in this region, where soil samples were collected.

The next highest contents of total organic carbon were found in the soils samples from hand-hoed (CAPM), post-emergence herbicide (HPOS), rotary tilling (ENRT) followed by no-weed control (SCAP), disk harrow (GRAD), and lowest was found in the soil from pre-emergence herbicide (Figure 1B). This low organic carbon condition was obviously due to the lack weed on the soil surface in the pre-emergence herbicide management system in agreements with other reports from tropical soil environments (Faria et al., 1998; Alcântara & Ferreira, 2000b; Araujo-Junior et al., 2011).

Published results reveal that weedy soil covers between coffee rows had great influences on the dynamics of total organic carbon content. Plant residues may influence the light soil fraction and thus the organic carbon content as reported by Ding et al. (2006) when these authors assessed the effect of cover crop management on chemical and structural composition of soil organic matter. The constant use of the pre-emergence herbicide for weed control in Dystroferric Red Latosol clay decreases significantly the total organic carbon content in the soil surface, because of the prevalence of soil without weed between the coffee rows. The effect of weed control with pre-emergence herbicide on total soil organic carbon was observed also in the 10–13 cm layer due the absence of weed roots (Figure 1B).

The different weed management system applied to coffee interrows influenced the soil bulk density and organic carbon content of the Latosol, in the 25-28 cm layer (Fig. 1A and 1B), when compared with the soil under natural forest (NAFT); however, when the soil samples were collected in center of the interrows, differences were not observed (Araujo-Junior et al., 2011). These authors observed that different weed management systems used in the interrows did not influenced soil bulk density and total organic carbon content of the Latosol, in the 25–28 cm layer, compared to the soil under natural forest. In our study, it is important highlight that the soil samples were collected in the traffic line of machines, and the total soil organic carbon content did not differ among the weed management systems in coffee plantation at the 25–28 cm depth (Figure 1B). However, Latosol samples from natural forest had greater total organic carbon content when compared to the soil under the

different weed management system in coffee plantation. It has been proposed that the conservation of soil organic matter is an essential to protection soil against compaction (Etana et al., 1997; Dexter, 2004; Zhang et al., 2005; Araujo-Junior et al., 2011).
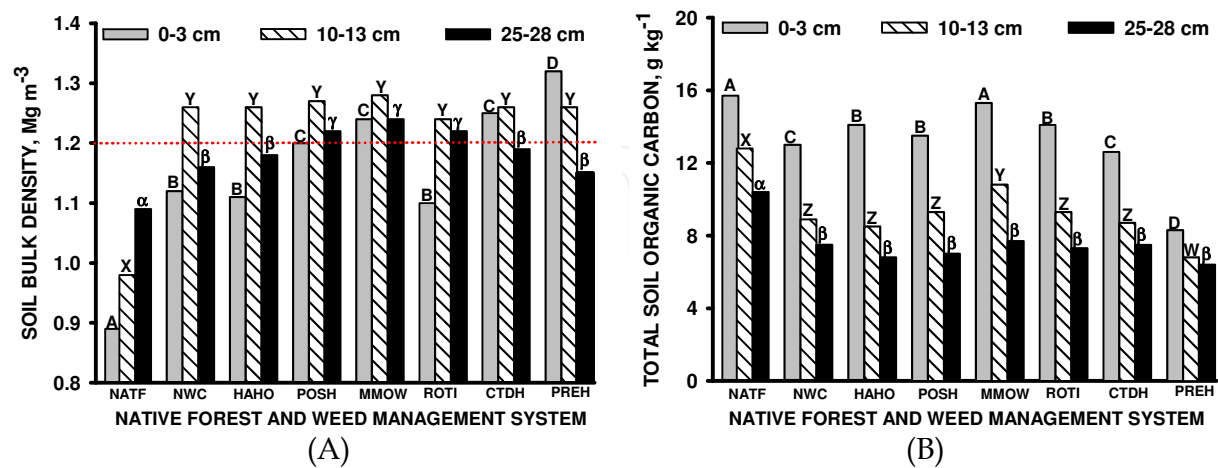

Fig. 1. Soil bulk density (A) and total soil organic carbon (B) of a Dystroferric Red Latosol in 0–3, 10–13 and 25–28 cm layers, affected by different weed management between coffee rows. NATF: natural forest; NWC: no-weed control between coffee rows; POSH: post-emergence herbicide; MMOW: mechanical mower; ROTI: rotary-tilling; CTDH: coffee tandem disk harrow; PREH: pre-emergence herbicide. Mean followed by equal letters compare the layers in the same weed management, and uppercase letters among the managements in the same depth of sampling, were not different, at 5% probability by the Scott-Knott test. Letters A to D compare 0-3 cm, X and Y compare managements at the 10-13 cm and Greek letters 25–28 cm depths. The red horizontal dotted line represents the critical soil bulk density for coffee root growth and soil structure sustainability estimate by Araujo-Junior et al. (2011) based on soil compression curves.

3.2 Total porosity and pore size distribution

Figure 2 shows the total porosity and pore size distribution of the Dystroferric Red Latosol (Oxisol) under native forest compared with the samples from the coffee plantation under different weed management system. We observed that samples taken from natural forest in the 0–3 cm depth have a higher total porosity (0.73 cm^3 cm^{-3}), macroporosity (0.44 cm^3 cm^{-3}) and lower microporosity (0.29 cm^3 cm^{-3}) when compared to the soil in different weed management system in the coffee plantation. For other depths (10–13 cm and 25–28 cm), the Latosol total porosity and pore size distribution were not different under natural forest and coffee plantation in the different weed management systems. Studies have been shown that under native forest the most Latosols found in Brazil with the gibbsite minerals content and high hematite contents on the clay fraction have percentage of macropores higher than 20% (Kemper & Derpsch, 1981; Ferreira et al., 1999; Oliveira et al., 2003a,b; Ajayi et al., 2009; Severiano et al., 2011).

Macropores are the pores in the soil in which water percolates due to gravity and their number is also measure of soil compaction (Kemper & Derpsch, 1981). In addition, macropores facilitates gas movement, thus it relates to the ability of the soil both to store and to transport gas (Stepniewski et al., 1994). These authors concluded that macroporosity of 25% (v/v) provides good aeration while in the 10–25% (v/v) range, there may be a

limitation to gas exchange under certain conditions and that air-filled porosities < 10% (v/v) are characteristic of deficient aeration.

The lowest macroporosities (0.08 cm³ cm⁻³) in the 0–3 cm depth (pores with effective diameter greater than 50 μm, drained from cores) were observed for the samples under mechanical mowing and coffee tandem disk harrowing weed management system (Figure 2). The soil compaction process reduces the large pores in size first (Hillel, 1980; Dexter, 2004; Pires et al., 2008; Ajayi et al., 2009; Severiano et al., 2011).
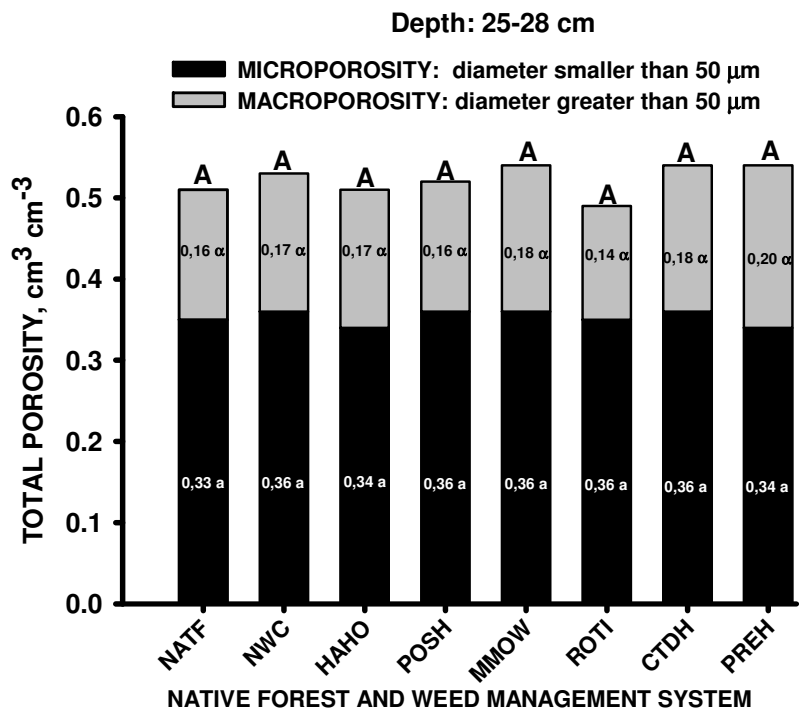
Depth: 25-28 cm
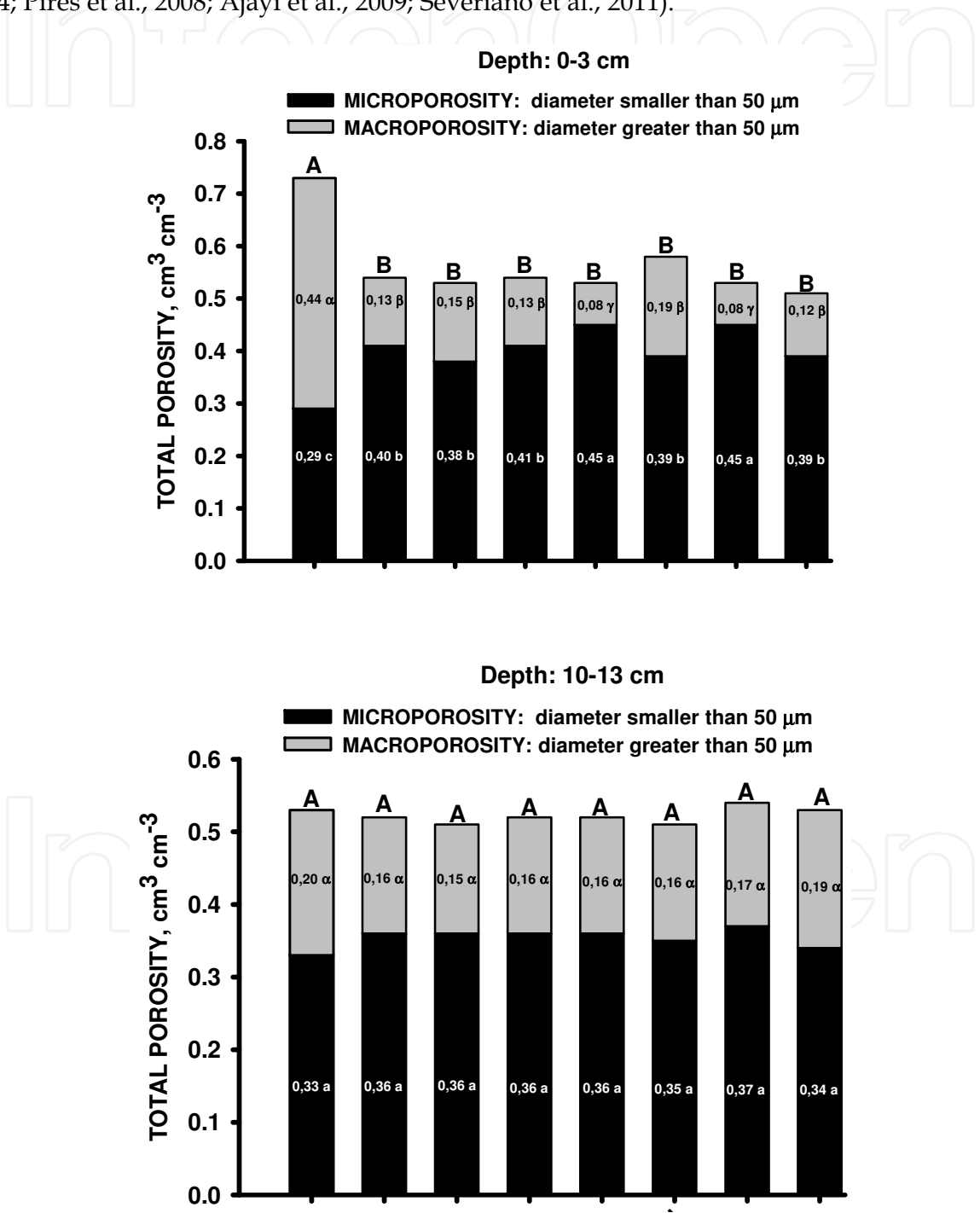
Fig. 2. Pore size distribution for a Dystroferric Red Latosol in 0–3, 10–13 and 25–28 cm layers, under natural forest and coffee plantation affected by different weed management between coffee rows. NATF: native forest; NWC: no-weed control between coffee rows; POSH: post-emergence herbicide; MMOW: mechanical mower; ROTI: rotary-tilling; CTDH: coffee tandem disk harrow; PREH: pre-emergence herbicide. Mean followed by equal letters compare the layers in the same weed management, and uppercase letters among the managements in the same depth of sampling, were not different, at 5% probability by the Scott-Knott test.

3.3 Soil-water retention curve

The soil-water retention curve defines the relationship between the soil matric potential and soil volumetric water content (Figure 3). This relationship may also assess the effect of weed management practices on soil structure. The differences between water retention behaviour for the soil samples collected at the interrows (center of the coffee rows, non-tracked soil) and the traffic line (wheel-tracked soil) at the 0 to 3 cm depth suggests that these curves are influenced by soil structure. The saturated water content (0.57 cm^3 cm^{-3}) for retention curve for traffic line decreased as a consequence of destruction of large pores or structural pores. On the other hand, the non-tracked interrow soil water retention curve revealed higher saturated water content (0.66 cm^3 cm^{-3}). As stated earlier, the large pores can be transformed into smaller pores and thus increase the soil-water holding capacity in low matric potential ($- 1500$ kPa). In this study, residual water content or water content at permanent wilting point ($- 1500$ kPa) increased in 0.04 cm^3 cm^{-3} in the traffic line as compared to interrows (Figure 3).

Recently, Dexter (2004) proposed to calculate the soil water retention curve parameters at inflection point (slope at inflection point, S-index) to assess soil physical quality. This author showed that the slope at inflection point governs directly many of the principal soil physical

quality and is a measure of soil microstructure that can be used as an index of soil physical quality. According to Pires et al. (2008) soil compaction decreases large pores followed by a rising amount of small pores, that committing soil physical quality decreases the S-index values (Dexter, 2004). They showed that large values for S-index indicating good soil physical quality and presence of structural pores.

Based on soil water retention curve behaviors for a Eutric Nitossol (430 g kg^{-1} clay) under coffee plantation Pires et al. (2008) assessed the effect of wetting and drying cycles. They found that the wetting and drying treatments did not affect the S-index for this soil. However, they showed that for the other soils S-index were affecting for the wetting and drying cycles.

INTERROWS: $\theta = 0,24 + (0,66 - 0,24)/[1+(1,1346 \times \Psi_m)^{1,7069}]^{0,4141}$ $R^2 = 0,99^{**}$

TRAFFIC LINE: $\theta = 0,28 + (0,57 - 0,28)/[1+(1,8066 \times \Psi_m)^{1,3355}]^{0,2512}$ $R^2 = 0,94^{**}$
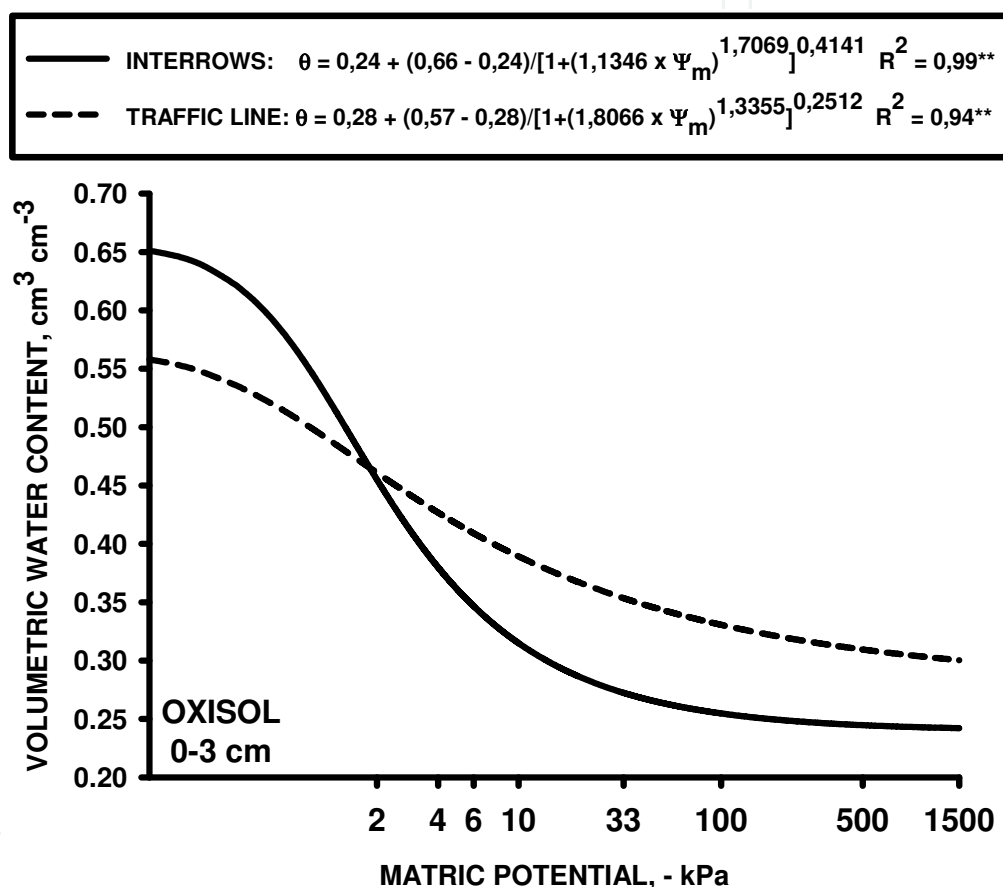

Fig. 3. Soil water retention curves for a Dystroferric Red Latosol in 0–3 cm in two sampling position interrows (no-wheel tracked soil) and traffic line (wheel-tracked soil).

3.4 Soil compressive behavior and load bearing capacity models

The soil compression curve is a conceptual and interpretative tool by which the compressive behaviour of the soil can be understood. The soil compression curve or stress-deformation curve can be described as a measure of soil deformation under given external loads (Holtz & Kovacz, 1981) (Figure 4) and defines the relationship between the logarithm of applied normal stress on the top of the sample and some parameter related to the packing state of soil; for example soil void ratio or soil bulk density (Casagrande, 1936; Larson et al., 1980; Holtz & Kovacs, 1981; Horn, 1988; Dias Junior & Pierce, 1995). This curve is divided into two

regions so-called: a region of plastic and unrecoverable deformation called the virgin compression curve, and a region of small, elastic and recoverable deformation called the secondary compression curve (Larson et al., 1980; Holtz & Kovacs, 1981; Dias Junior & Pierce, 1995; Gregory et al., 2006). The point that separates these two regions in a compression curve is the precompression stress or preconsolidation pressure (σp) depending on if air or water is being eliminated from the soil, and can be variously defined.

In this study, we assumed, the precompression stress as indicator of internal strength of soils, which resulted from pedogenetic processes, anthropogenic effects, or hydraulic site-specific conditions (Horn et al., 2004) the maximum vertical overburden stress that particular sample has sustained in the past (Holtz & Kovacs, 1981) or as a predictor of the critical strength at which root elongation ceases (Römkens & Miller, 1971). This parameter is influenced by the initial soil volumetric water content (θ), initial soil bulk density (Bd), total organic carbon (TOC), soil structure and stress history, as it relates to the different weed management in coffee plantation.

The stress in a logarithmic scale versus strain data were then used to construct the soil compression curves (Larson et al., 1980), from which the precompression stress (σp) were determined (Figure 4) following the procedure of Dias Junior & Pierce (1995). In this procedure, precompression stress was estimated as the intersection of two lines: the regression line obtained for the first two (for soil samples with initial volumetric water content higher than matric potential – 100 kPa) or four points (for soil samples with matric potential lower or equal – 100 kPa) of the applied stress sequence in the secondary compression portion of the compression curve and the extension of the virgin compression line determined from the points associated with applied stress of 800 and 1600 kPa (Figure 4).
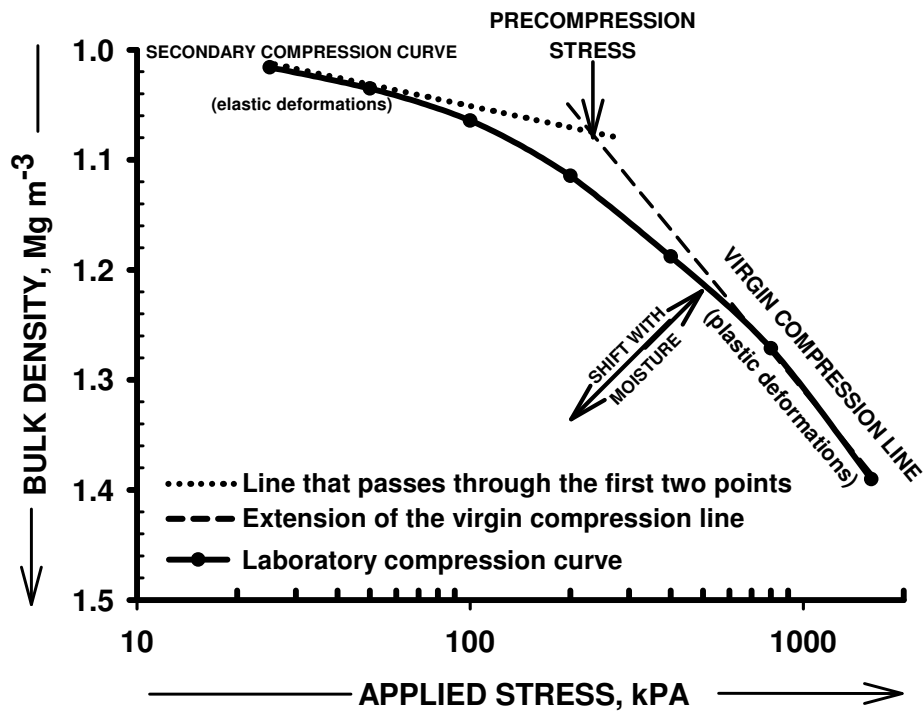

Fig. 4. Soil compression curve illustrating the position of the precompression stress
Source: "From Dias Junior, 1994"

Soil load bearing capacity has been defined as the capability of a soil structure to withstand stresses induced by field traffic without changes in the three-dimensional arrangement of its constituent soil particles (Alakukku et al., 2003). Soil load bearing capacity models (LBC) represents mathematically the relationship between soil volumetric water content (θ) and soil precompression stress (σp) and may be described by the Equation 1 (Dias Junior, 1994). In this model, the precompression stress decreases exponentially with the increases in the volumetric soil water content.

$$\sigma_p = 10^{(a + b\theta)}$$ (1)

Where, precompression stress (σp), estimated linear "a" and angular "b" coefficients and θ the initial volumetric soil water content. All the models obtained for the Dystroferric Red Latosol were significant at 1% probability level, for t-Student test and the coefficient of determination (R^2) ranged from 0.75 to 0.96 (Table 2).

The estimated linear "a" and angular "b" coefficients of the load bearing capacity models values varied from 2.57 for the soil under native forest at 0–3 cm depth to 2.89 for the soil samples collected from rotary tiller at 25–28 cm depth, and from -1.60 for the soil samples under pre-emergence herbicide at 25–28 cm depth, to - 0.71, for the soil samples collected from native forest at 0–3 cm depth (Table 2). Others studies done in Brazilian Latosols and Ultisols (Silva & Cabeda, 2006; Oliveira et al., 2003a; Kondo & Dias Junior, 1999) are in agreement with this results, which found lowest linear coefficients for soils under native forest when compared to the soil under different tillage management. The soil samples collected from native forest presented lower soil bulk density, microporosity and higher total organic carbon content, total porosity and macroporosity (Figures 1 and 2) due to the lack of anthropogenic activity and stress history. These findings suggest that the fitted parameter, "a" is interrelated to the packing of the solid particles expressed by soil bulk density and air-filled porosity (macropores) which affect the pore water pressure.

In all the models, the dependence of soil precompression stress on the water content in the soil was displayed. It was observed that the strength of the Latosol soil samples reduces although not linearly, with increases in the water content of the soil. The observation was consistent with results from several studies on the strength of soil samples (Kondo & Dias Junior, 1999; Peng et al., 2004; Dias Junior et al., 2005; Araujo-Junior et al., 2008, 2011).

Reported results from soil samples from three Ultisols under subtropical climate, Peng et al. (2004) also suggested that precompression stress decreases in exponential way with the initial water content. These authors suggest that the parameter "a" indicates the intrinsic strength of dry soil and the parameter "b" influences of soil properties such as soil texture and organic matter on the soil strength.

3.4.1 Influence of weed management system on soil load bearing capacity

To assess the influence of the adoption of different weed management on soil load bearing capacity, undisturbed soil samples collected from native forest and coffee plantation submitted to different weed management system were subjected to uniaxial compression test to obtain the soil compression curves. This load bearing capacity model was used to verify possible effects of different weed management systems on soil structure. This model is based on stress history or either, of the stress and other changes that have occurred during

their history, and these changes are preserved in the soil structure (Casagrande, 1932 cited by Holtz & Kovacs, 1932).

Native forest and weed management	a	b	R^2	n
Depth: 0–3 cm				
Native forest	2,57	- 0,71	0,80**	15
No-weed control between coffee rows	2,65	- 1,26	0,96**	15
Hand hoe	2,82	- 1,56	0,84**	15
Post-emergence herbicide	2,72	- 0,92	0,92**	15
Mechanical mower	2,86	- 1,19	0,83**	15
Rotary-tilling	2,74	- 1,14	0,79**	14
Coffee tandem disk harrow	2,73	- 0,84	0,77**	15
Pre-emergence herbicide	2,78	- 1,35	0,86**	15
Depth: 10-13 cm				
Native forest	2,61	- 0,90	0,77**	15
No-weed control between coffee rows	2,77	- 1,26	0,84**	15
Hand hoe	2,77	- 1,05	0,86**	15
Post-emergence herbicide	2,77	- 1,43	0,87**	15
Mechanical mower	2,79	- 1,37	0,82**	15
Rotary-tilling	2,82	- 1,24	0,81**	15
Coffee tandem disk harrow	2,71	- 0,92	0,77**	15
Pre-emergence herbicide	2,83	- 1,49	0,78**	14
Depth: 25-28 cm				
Native forest	2,66	- 1,11	0,90**	14
No-weed control between coffee rows	2,66	- 0,93	0,82**	15
Hand hoe	2,76	- 1,40	0,94**	15
Post-emergence herbicide	2,86	- 1,51	0,86**	15
Mechanical mower	2,80	- 1,26	0,75**	15
Rotary-tilling	2,89	- 1,45	0,83**	15
Coffee tandem disk harrow	2,76	- 1,27	0,84**	14
Pre-emergence herbicide	2,81	- 1,60	0,83**	14

Table 2. Linear (a) and angular (b) coefficients of the load bearing capacity models $[\sigma_P = 10^{(a + b\theta)}]$, with respective coefficients of determination (R^2), and number of undisturbed soil samples (n) collected at 0–3, 10–13 and 25–28 cm depths in the traffic line in a Dystroferric Red Latosol (Oxisol) under native forest and coffee plantation submitted to different weed management systems.

The load bearing capacity models of the sample collected from different land uses (native forest and coffee plantation), but at different depths, and those of the various weed management systems were compared in multiple scatter plots (Fig. 5 – 7) and using the test of homogeneity for comparison of regression lines (Snedecor & Cochran, 1989). In the multiple scatter plots, the entire soil moisture and the corresponding preconsolidation value data in the different sites are pulled together on a single graph. For the homogeneity test, two models are picked and compared together by examining the intercept (a), slope (b) and the homogeneity parameter data (F). To obtain a and b values in each model for comparison, the model equation in the exponential form (Eq. 1) was transformed into a linear model by computing the logarithm of both sides of the equation giving equation of the form (Eq. 2) (Dias Junior et al., 2005; Araujo-Junior et al., 2011).

$$\log \sigma_p = \log 10^{(a+b\theta)} = \log \sigma_p = a + b\theta \qquad (2)$$

We observed that soils under natural forest and no-weed control exhibited the lowest load bearing capacities at the 0-3 cm depth when compared with those under the varied weed management system used in coffee plantation (Figure 5 to 7). This observation can be associated with initial soil bulk density and soil organic carbon content (Figure 1A and 1B) and be associated with the absence of stress history and anthropogenic activities on the soil under native forest. On the other hand, the weed control using mechanical mower exhibited the highest load bearing capacity at that depth (Figure 5). The final results are presented in Fig. 5 for the models of the sample collected from different weed management systems at depth 0–3 cm depth. Homogeneity tests of the regression equations (Snedecor & Cochran, 1989) indicated that the soil under hand hoeing and pre-emergence herbicide weed management; post-emergence herbicide and coffee tandem disk harrow weed management had the similar load bearing capacities at the 0-3 cm depth (Table 3). Therefore, the dataset of the homogeneous models were combined and a new equation was fitted to each data set, considering all the values of preconsolidation pressure and volumetric soil water content for these treatments (Figure 5). Generally, it was observed that the load bearing capacity for the Dystroferric Red Latosol under the different weed management systems at the soil surface(0-3 cm depth) decreases in a following order: mechanical mower > post-emergence herbicide = coffee tandem disk harrow > rotary tiller > hand hoeing = pre-emergence herbicide > natural forest > no-weed control (Figure 5). The highest soil load bearing capacity was observed for the Latosol under mechanical mower in 0-3 cm depth (Fig. 5). Others studies, have been shown that high traffic intensity necessary to satisfactory weed control in coffee plantation throughout the year (5 to 6 times) increases the risk of soil compaction (Silveira & Kurachi, 1984; Alcântara & Ferreira, 2000b; Silva et al., 2006) mainly in the rainy season (October to March) when the soils has high soil water content and consequently lower load bearing capacity (Silva et al., 2006) increases the soil susceptibility to compaction. On the other hand, when soil is drier present higher resistance to compression and high load bearing capacity that decreases soil susceptibility to compaction (Dias Junior et al., 2005; Araujo-Junior et al., 2008; 2011).

Our results suggested the mechanical mower had a greater potential for causing soil compaction due to high traffic intensity to satisfactory weed control through the year (5 operations) and this operation must be accomplished when the soil has water content lower than 0.30 cm^3 cm^{-3} to minimize or avoid additional soil compaction.

MANAGEMENT WEED SYSTEM		F	
	F	Angular coefficient, b	Intercept of regression, a
Depth: 0-3 cm			
HAND HOE vs PRE-EMERGENCE HERBICIE	H	ns	ns
HAND HOE and PRE-EMERGENCE HERBICIDE vs ROTARY-TILLING	H	*	ns
HAND HOE and PRE-EMERGENCE HERB. vs MECHANICAL MOWER	H	**	ns
HAND HOE and PRE-EMERGENCE HERBICIDE vs NATIVE FOREST	H	**	ns
HAND HOE and PRE-EMERGENCE HERBICIDE vs NO-WEED CONTROL	H	*	*
POST-EMERGENCE HERBICIDE vs DISK HARROW	H	ns	ns
POST-EMERGENCE HERBICIDE and DISK HARROW vs ROTARY-TILLING	H	ns	**
POST-EMERGENCE HERBICIDE and DISK HARROW vs MECHANICAL MOWER	H	*	ns
POST-EMERGENCE HERBICIDE and DISK HARROW vs HAND HOE and PRE-EMERGENCE HERBICIDE	H	**	**
POST-EMERGENCE HERBICIDE and DISK HARROW vs NATIVE FOREST	H	*	**
POST-EMERGENCE HERBICIDE and DISK HARROW vs NO-WEED CONTROL	H	ns	**
MECHANICAL MOWER vs ROTARY-TILLING	H	**	**
MECHANICAL MOWER vs NO-WEED CONTROL	H	ns	**
NATIVE FOREST vs NO-WEED CONTROL	H	**	ns
NATIVE FOREST vs ROTARY-TILLING	H	*	ns
NATIVE FOREST vs MECHANICAL MOWER	H	**	**

H: homogeneous; ** significant at 1 % probability level; * significant at 5 % probability level; ns: not significant

Table 3. Comparison of the load bearing capacity models for homogeneity of a Dystroferric Red-Latosol at 0-3 cm depth under native forest and in a coffee plantation submitted to different weed management systems

According to Yang et al. (2007) the weed control in an orchard citrus by mowing three times during the growing season could improve soil and mitigate negative effects of weeds on crops. In the study by Zhang et al. (2006), it was observed that the first three passes of the tractor caused the largest increments in the mechanical resistance of the soil in the first 12cm depth. In conservation tillage systems, no - till management promotes higher soil organic carbon content and contribute to aggregate stability under loading, due to improved structural stability (Silva & Cabeda, 2006). Similarly, others authors have shown that increases in the soil organic carbon content reduces the adverse effects of soil compaction

(Etana et al., 1997) while increasing compressibility due to higher soil resilience (Zhang et al., 2005).

The hand hoeing, pre-emergence herbicide and rotary tilling weed management systems load bearing capacities models were intermediate in the behaviour for the studied depth relative to mechanical mowing (highest) and no weed control between coffee rows (lowest). At this depth, our results for the load bearing capacity models were similar to the obtained by Kurachi & Silverira (1984) starting from medium profiles of mechanical resistance of the profile of the soil under different weed management systems. These authors also observed that the mechanical mower was the implement that impact more on the soil strength, followed by the herbicide sprayer and the rotary tilling.
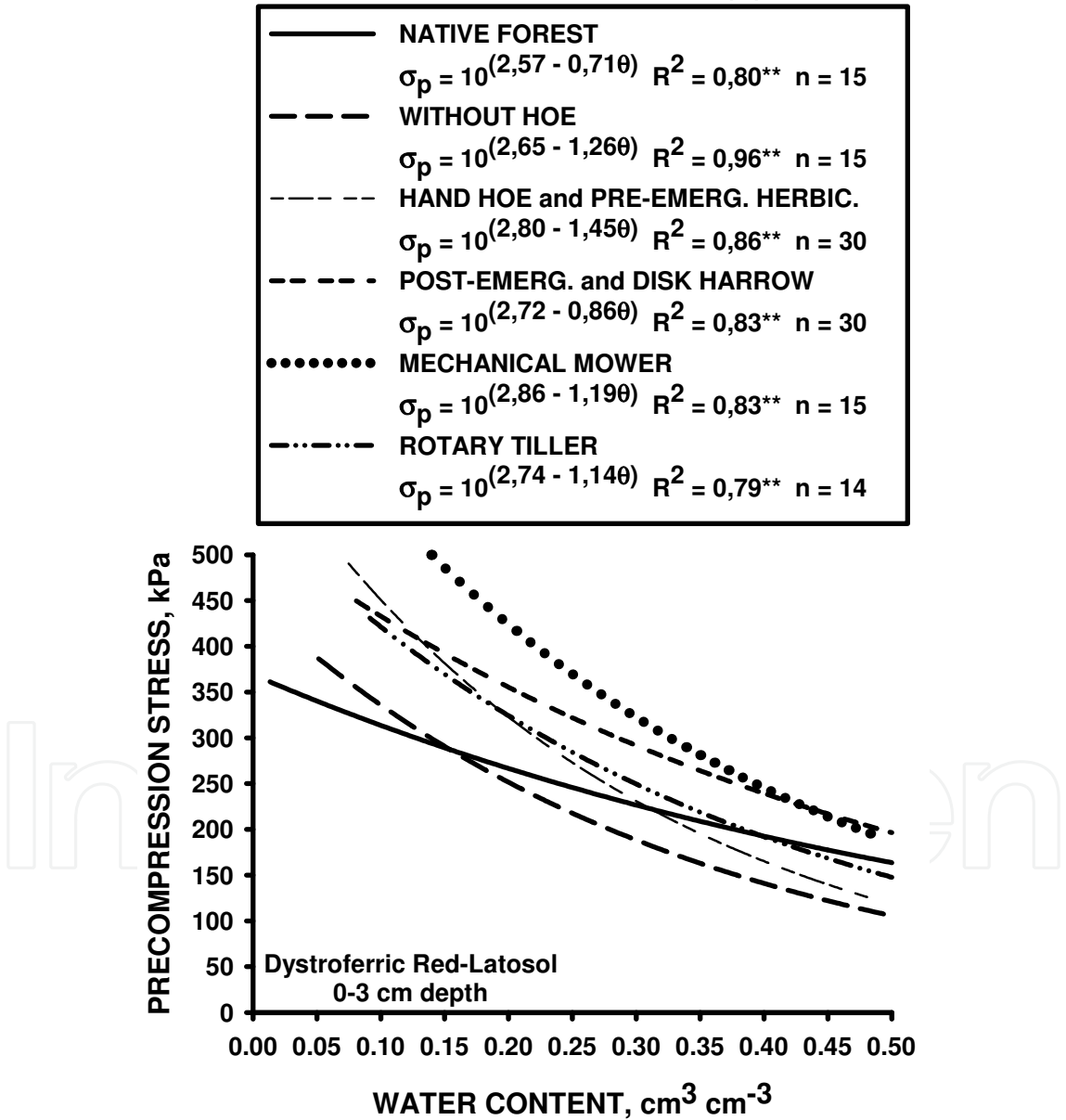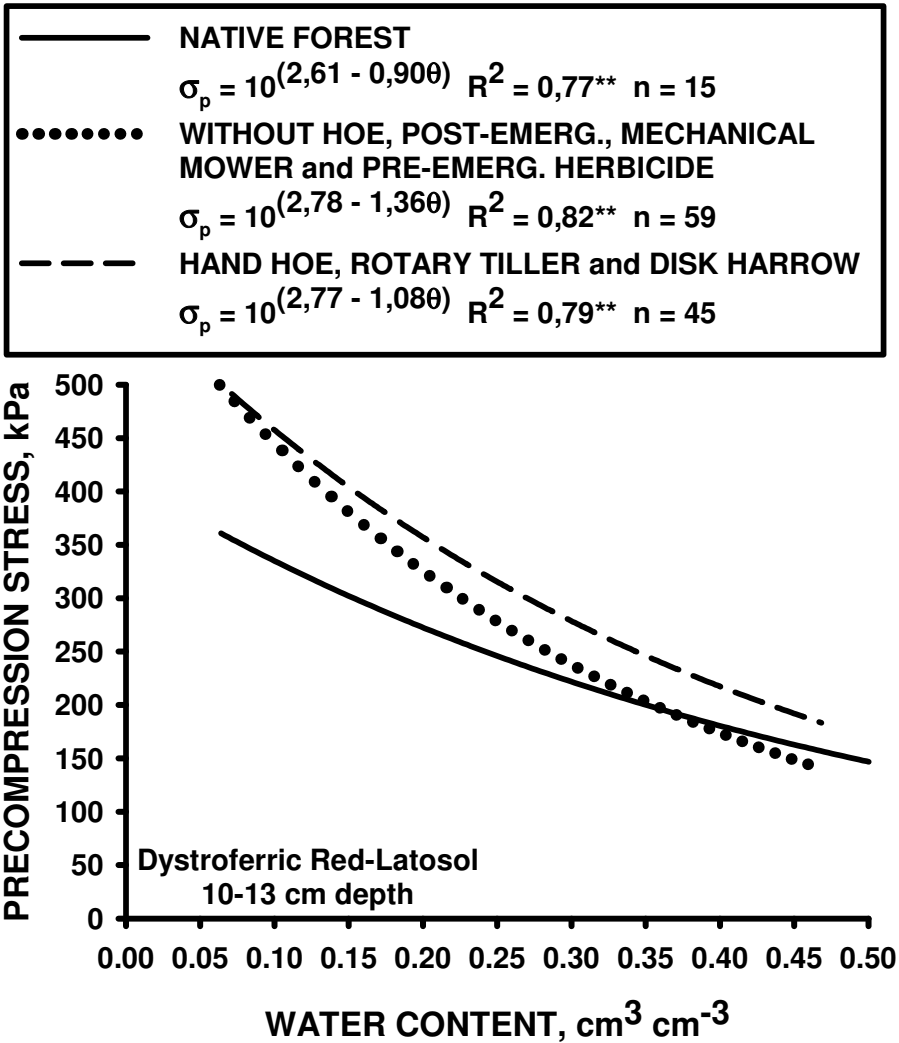

Fig. 5. Load bearing capacity models of a Dystroferric Red Latosol in 0–3 cm layer, cultivated with coffee plants affected by different weed management in interrows of the coffee plantation.

The homogeneity tests of the regression equations for the samples collected in the 10-13 cm depths showed that there were two homogeneous dataset. The mechanical mowing, pre-emergence herbicide, no-weed control and post-emergence herbicide; and rotary-tilling exhibited similarity, while hand hoeing, and coffee tandem disk harrowing were similar (Table 4). Therefore, for each homogeneous dataset, a new equation was fitted, combining all the values of preconsolidation pressure and volumetric soil water content (Figure 6).

MANAGEMENT WEED SYSTEM	F	F	
		Angular coefficient, b	Intercept of regression, a
Depth: 10-13 cm			
MECHANICAL MOWER vs PRE-EMERGENCE HERBICIDE	H	ns	ns
MECHANICAL MOWER and PRE-EMERGENCE HERBICIDE vs NO-WEED CONTROL	H	ns	ns
MECHANICAL MOWER and PRE-EMERGENCE HERBICIDE and NO-WEED CONTROL vs POST-EMERGENCE HERBICIDE	H	ns	ns
ROTARY-TILLING vs HAND HOE	H	ns	ns
ROTARY-TILLING and HAND HOE vs DISK HARROW	H	ns	ns
ROTARY-TILLING and HAND HOE and DISK HARROW vs NATIVE FOREST	H	**	**
MECHANICAL MOWER and PRE-EMERGENCE HERBICIDE and NO-WEED CONTROL vs POST-EMERGENCE HERBICIDE vs NATIVE FOREST	H	**	ns
MECHANICAL MOWER and PRE-EMERGENCE HERBICIDE and NO-WEED CONTROL vs POST-EMERGENCE HERBICIDE vs ROTARY-TILLING and HAND HOE and DISK HARROW	H	*	**

H: homogeneous; ** significant at 1 % probability level; * significant at 5 % probability level; ns: not significant

Table 4. Comparison of the load bearing capacity models for homogeneity of a Dystroferric Red-Latosol at 10-13 cm depth under native forest and in a coffee plantation submitted to different weed management systems.

In general, at 10-13 cm depth the load bearing capacity models for studied area under varying weed management systems were similar and decreased in the following order: hand hoeing = rotary tilling = coffee tandem disk harrow > no-weed control = post-emergence herbicide = mechanical mower = pre-emergence herbicide > natural forest (Figure 6). These responses are associated with lowest soil bulk density value and the greatest soil organic carbon content of the soil under natural forest (Figure 1A and 1B). The lack of anthropogenic activities in the soil under natural forest provides the greater soil organic carbon content and smaller values of soil bulk density, which contribute to smaller

values of precompression stress consequently, smaller load bearing capacity at all soil water content. The weed management systems of hand hoeing, rotary tilling and coffee tandem disk harrow had higher soil load bearing capacity at all soil water content (Figure 6). The disturbed soil on soil surface for these weed management favor the stress distribution to 16-21 cm depth (Araujo-Junior et al., 2011), increases the soil load bearing capacity of the samples at the 10-13 cm depth, being the area mainly affected by the distributed stresses (Figure 6).

Fig. 6. Load bearing capacity models of a Dystroferric Red Latosol in 10–13 cm layer, cultivated with coffee plants affected by different weed management in interrows of the coffee plantation.

At the 25-28 cm depth, the weed management systems sets consisting of mechanical mowing , post-emergence herbicide and rotary tilling; hand hoeing, pre-emergence herbicide and coffee tandem disk harrow; resulted in homogenous load bearing capacity models (Table 5). Therefore, for each homogeneous set, the data set consisting all the values of preconsolidation pressure and volumetric soil water content were combined and a new equation was fitted (Figure 7). We observed that the load bearing capacity of the soils were similar and decreased in the following order: post-emergence herbicide = mechanical

mower = rotary tilling > hand hoeing = pre-emergence herbicide = coffee tandem disk harrow > no-weed control > natural forest (Figure 7).

MANAGEMENT WEED SYSTEM		F	
	F	Angular coefficient, b	Intercept of regression, a
Depth: 25–28 cm			
MECHANICAL MOWER vs POST-EMERGENCE HERBICIDE	H	ns	ns
MECHANICAL MOWER and POST-EMERGENCE HERBICIDE vs ROTARY-TILLING	H	ns	ns
HAND HOE vs PRE-EMERGENCE HERBICIDE	H	ns	ns
HAND HOE and PRE-EMERGENCE HERBICIDE vs DISK HARROW	H	ns	ns
HAND HOE and PRE-EMERGENCE HERBICIDE and DISK HARROW vs NO-WEED CONTROL	NH	**	**
HAND HOE and PRE-EMERGENCE HERBICIDE and DISK HARROW vs NATIVE FOREST	NH	**	ns
HAND HOE and PRE-EMERGENCE HERBICIDE and DISK HARROW vs MECHANICAL MOWER and POST-EMERGENCE HERBICIDE and ROTARY-TILLING	NH	**	**
MECHANICAL MOWER and POST-EMERGENCE HERBICIDE and ROTARY-TILLING vs NO-WEED CONTROL	H	**	*
MECHANICAL MOWER and POST-EMERGENCE HERBICIDE and ROTARY-TILLING vs NATIVE FOREST	H	**	*
NATIVE FOREST vs NO-WEED CONTROL	H	ns	**

H: homogeneous; ** significant at 1 % probability level; * significant at 5 % probability level; ns: not significant

Table 5. Comparison of the load bearing capacity models for homogeneity of a Dystroferric Red-Latosol at 25-28 cm depth under native forest and in a coffee plantation submitted to different weed management systems.

The weed management systems consisting of post-emergence herbicide, mechanical mowing and rotary tilling resulted in most comparisons, higher soil load bearing capacity for the Latosol, indicating that the effect of the traffic of machines in mechanical weed control induced the compaction of the soil in sub-soil region. Kurachi & Silveira (1984) suggest that the weed managements systems that involve the disturbance of the soil had the tendency to increase compaction at the surface; when there is no disturbance, increase compaction is more accentuated starting from the depth of operation of the equipment. However, our result show that the herbicide applicator and mechanical mower as well as

rotary tilling increased the soil's mechanical resistance in the moisture levels of 15 cm^3 cm^{-3} and 20 cm^3 cm^{-3}, when compared to hand hoeing. Looking at data presented in Figure 7, it is possible to conclude that, even with the absence of mechanical soil disturbance weed management systems, the soil can still be compacted when wet, when stresses travel up to a depth of 25-28 cm (Figure 7).
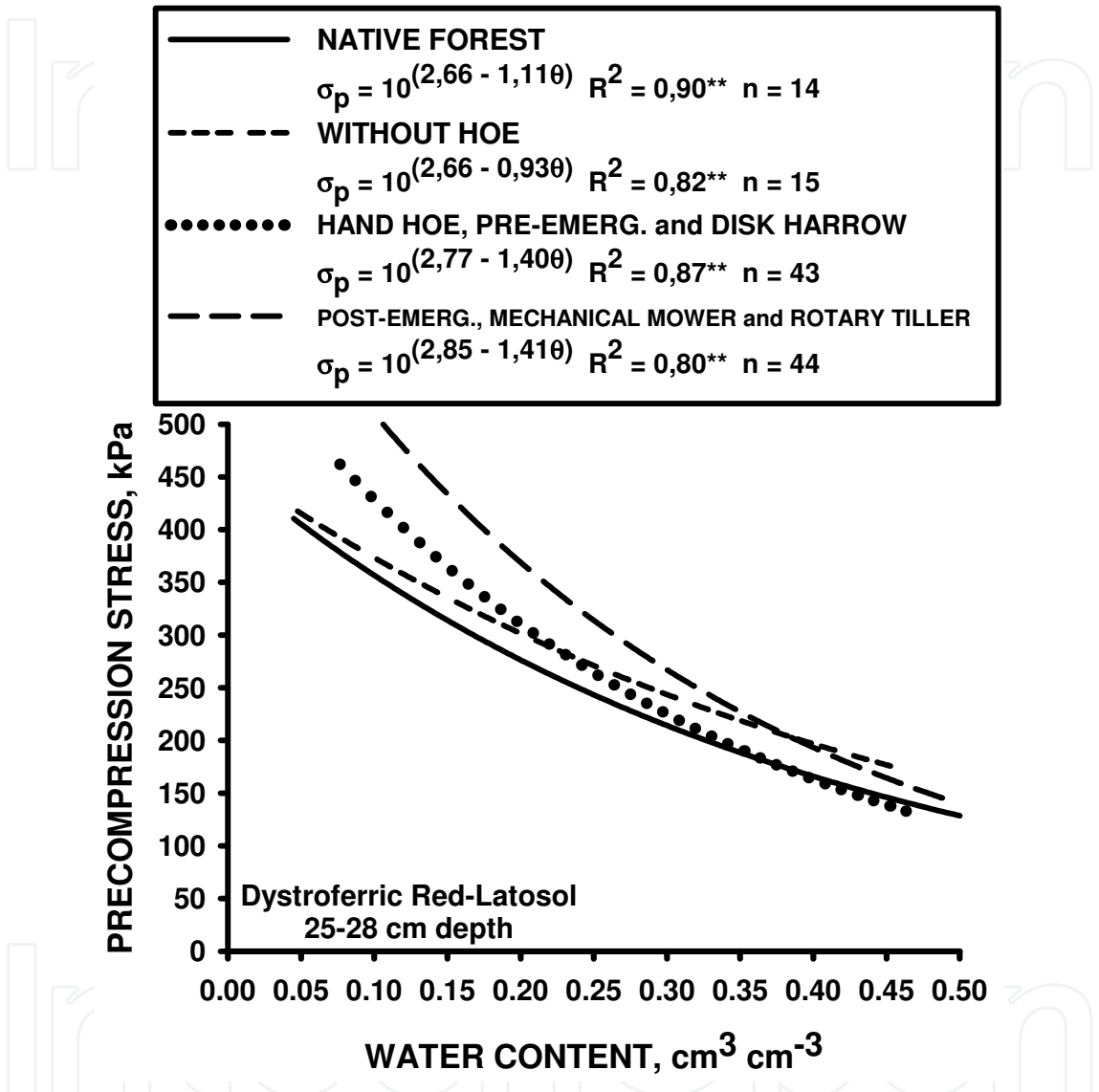
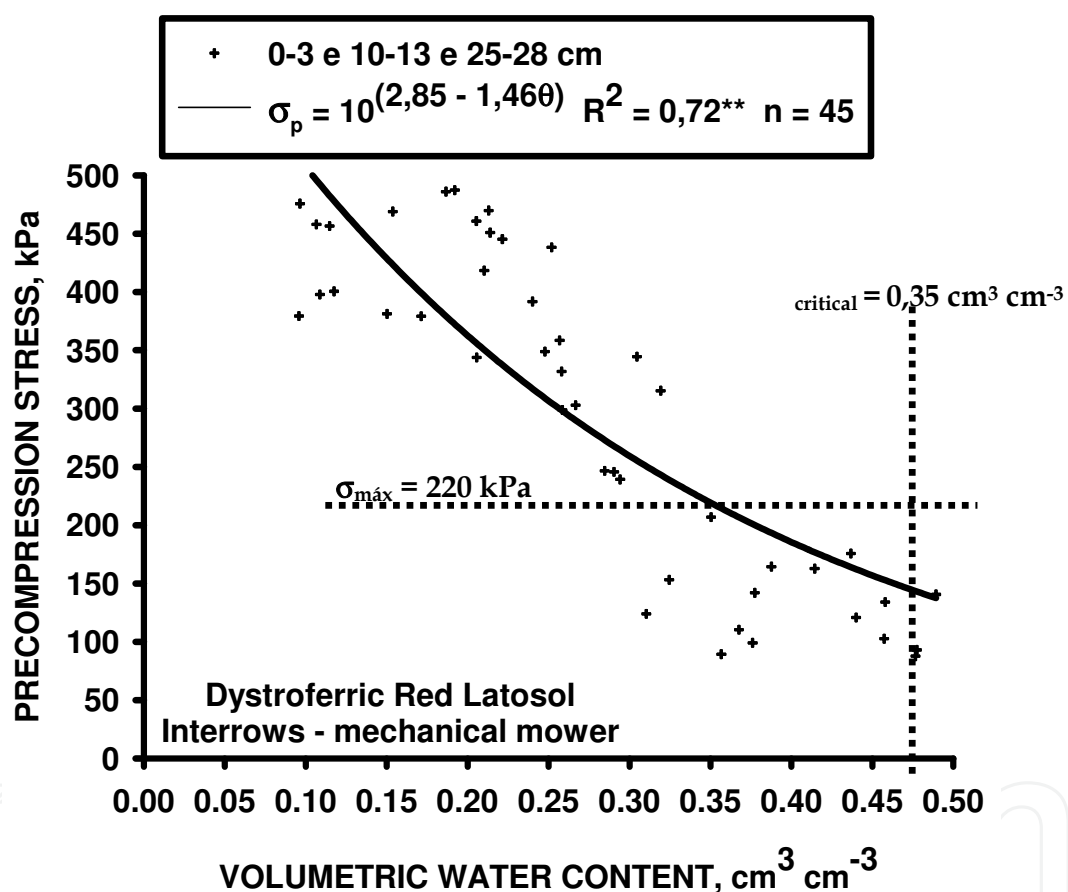

Fig. 7. Load bearing capacity models of a Dystroferric Red Latosol in 25–28 cm layer, cultivated with coffee plants affected by different weed management in interrows of the coffee plantation.

3.4.2 Critical volumetric soil water content for traffic of tractor based on soil load bearing capacity

According to Hillel (1980) soil moisture is the most important soil physical properties to determine soil-machine interactions. This soil physical property also, governs soil deformation when submitted to external loads (Dias Junior, 1994; Dias Junior & Pierce, 1996). To determine the critical volumetric soil water content (θcritical) for traffic of

machines and tools, we considered only those stress that can cause additional soil compaction or change the initial state of the soil structure, and are considered that stress do not exceed internal strength expressed by precompression stress (Araujo-Junior et al., 2011). The maximum vertical stress exerted by the tractor and equipments (σ_{max}) and the stress distribution in various wheeled and soil conditions were obtained using the Tyres/Tracks and Soil Compaction-TASC program (Diserens, 2005).

The maximum stress exerted by a tractor Valmet® model 68 was 220 kPa for front tyres 6-16 inflation pressure 172 kPa. The lowest critical water content was 0.27 cm³ cm⁻³ for the Dystroferric Red Latosol in the without hoe no inter-rows control at the 0–3 cm depth and the higher 0.48 cm³ cm⁻³ for the soil managed with pre-emergence herbicide in the 0–3 cm layer.

Fig. 8. Soil load bearing capacity models of a Dystroferric Red Latosol in 0–3, 10–13 and 25–28 cm layers, cultivated with coffee plants affected by different weed management in interrows in coffee plantation. ROÇA: mechanical mower. The dotted vertical line represents critical water content (θcritical) for tractor traffic above the soil under mechanical mower management. The dotted horizontal line represents the maximum vertical stress exerted by a tractor (σmax).

Our results show that load bearing capacity models might be useful to assess the effect of the weed management on soil strength or inherent ability of the soil samples to withstand applied pressure without degrading their structure. Also, this soil mechanic approach could

be used to define the optimum moisture content for machine traffic without degrading the soil structure.

4. Conclusions

Our results reveal that the weed management system and traffic by machines had a great influence on soil physical quality attributes, mainly on the surface soil (0–3 cm depth) on the inherent strength. The greatest changes in the Latosol structure were observed under mechanical mowing, disk harrowing and pre-emergence herbicide weed management. These observations are related to the applied stress by the machines and direct raindrop impacts to bare soil systems that favored crust formation, thereby increasing the soil strength on the soil surface. In addition, weed control practices that result in the total removal of the soil cover was more prone to compaction due to applied soil stress by machines and equipments.

The soil load bearing capacity and the water content at the time of the traffic machines are the most important soil physical properties; thus these attributes must be considered to minimize additional soil compaction and soil structure damage on coffee plantations under different weed management systems. Recommendations for the sustainable weed management system in coffee plantation must consider the inherent internal strength of the soil expressed by precompression stress.

5. Acknowledgments

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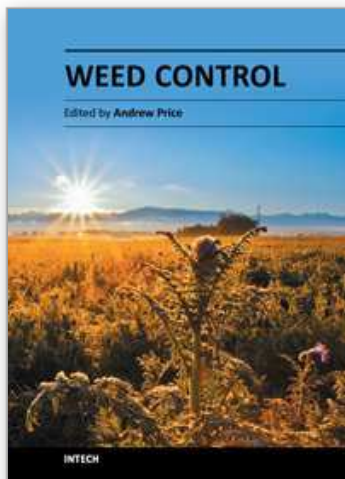
Weed Control

Edited by Dr. Andrew Price

Crop loss due to weeds has challenged agricultural managers since man began to develop the first farming systems. In the past century, however, much progress has been made to reduce weed interference in crop settings through effective yet mostly non-sustainable weed control strategies. With the commercial introduction of herbicides during the mid-1900's, advancements in chemical weed control tactics have provided efficient suppression of a broad range of weed species for most agricultural practices. Currently, with the necessity to design effective sustainable weed management systems, research has been pushing new frontiers on investigating integrated weed management options including chemical, mechanical as well as cultural practices. Author contributions to Weed Science present significant topics of research that examine a number of options that can be utilized to develop successful and sustainable weed management systems for many areas of crop production

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