A Soil Mechanics Approach to Study Soil Compaction and Traffic Effect on the Preconsolidation Pressure of Tropical Soils

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A SOIL MECHANICS APPROACH TO STUDY SOIL COMPACTION

Introduction

The intensive use of the soil without moisture control has been causing dissemination of the soil compaction (Pedrotti and Dias Junior, 1996), due to the increase of the traffic of agricultural machines through the year (Hill and Meza-Montalvo, 1990; Muller et al., 1990), causing in consequence, a reduction of the productivity in the areas of intense traffic (Stone, 1987).

Soil compaction has been identified as one of the leading problem causing soil degradation (Canillas and Salokhe, 2002). Different soil uses has been altering the physical and mechanical soil properties (Barnes et al., 1971; Gupta et al., 1985; Larson et al., 1989; Soane and van Ouwerkerk, 1994; Dias Junior and Pierce, 1996ab, Dias Junior and Miranda, 2000, Horn et al., 2000; Dias Junior, 2000), causing soil compaction and restricting root penetration due to the insufficient root turgor pressure to overcome the mechanical resistance of the soil (Gysi, 2001). Soil compaction increase bulk density and soil strength (Taylor, 1971; Lebert et al., 1989; Hill and Meza-Montalvo, 1990; Lebert and Horn, 1991; Dias Junior et al., 1999, Arvidsson, 2001; Ishaq et al., 2001); decrease total porosity, size and continuity of the pores (Hillel, 1982; Smucker and Erickson, 1989; Servadio et al., 2001) and limit nutrient uptake, water infiltration and redistribution, gas exchange, seedling emergency and root development (Tardieu, 1988; Smucker and Erickson, 1989; Bicki and Siemens, 1991; Dürr and Aubertot, 2000, Arvidsson, 2001; Ishaq et al., 2001) resulting in decreased yields (Arvidsson, 2001; Radford et al., 2001; Dauda and Samari, 2002), increased erosion and increased power requirement for tillage (Stone, 1987, Canillas and Salokhe, 2002).

In tropical conditions, the soil compaction process has been occurring in annual crops due to tillage and harvest operation is carried out when the soil surface is wetter than optimal for wheel traffic (Silva et al., 1986, Dias Junior, 1997); in pasture, due to the excessive trampling of the cattle (Kondo and Dias Junior, 1999) and in forest areas due to the traffic of the harvest operations and wood transport under inadequate soil water conditions (Dias Junior et al., 1999; Dias Junior, 2000).

On the other hand, with the standardization of specific legislation regarding the use of natural resources, the companies involved in this activity type, should adapt their activities in a way to match sustainable development, avoiding therefore, the degradation of their areas. Thus, a consensus of which soil physics or mechanics property should be used as a universal indicator of soil structure sustainability is needed. Gupta and Raper (1994), suggested that there is a scarcity of reliable information concerning soil compaction that can be widely used to develop guidelines to determine: a) the maximum pressure a specific soil can withstand over a range of water content and b) the range of applied stresses and moisture contents that are conducive to excessive soil compaction.

In spite of this, there are evidences in literature indicating that preconsolidation pressure or precompression stress (σ_p) is an indication of soil strength (Arvidsson, 2001) and of the maximum previously applied stress sustained by a soil and defines the limit of elastic deformation in the soil compression curves (Holtz and Kovacs, 1981, Dias Junior and Pierce, 1995; Defossez and Richard, 2002), and may be used as a quantitative indicator of soil structure sustainability (Dias Junior et al., 1999) and to estimate, root growth (Römkens and Miller, 1971). Thus, in agriculture, application of stress greater than the precompression stress should be avoid (Gupta et al., 1989; Lebert and Horn, 1991; Defossez and Richard, 2002). Therefore, changes in σ_p as a function of moisture content is important for root growth and also to assess the load support capacity of the soil.

Although, several researchers (Barnes et al., 1971; Gupta et al., 1985; Larson et al., 1989; Soane and van Ouwerkerk, 1994; Dias Junior and Pierce, 1996ab, Dias Junior and Miranda, 2000; Horn et al., 2000) had already quantified the soil management effect in the soil physics properties, there is a need for a methodology that predicts the maximum stress that a soil can withstand over a range of water contents without causing soil structure degradation.

Inside of this context, Dias Junior (1994) seeking for a property that might be used as an indicator of soil management sustainability, developed a methodology that may be used to predict: a) the maximum pressure that a specific soil can withstand over a range of water content without additional soil compaction occurs and b) the range of applied stresses and water content that are conducive to additional soil compaction. Therefore, in this notes it will be present the development of this methodology and its application in studies of structure sustainability of some tropical soils.

Methodology Development

The soil compression curves obtained from laboratory compressibility test are frequently used in compaction studies (Larson et al., 1980; Larson and Gupta, 1980; Bingner and Wells, 1992; O'Sullivan, 1992; MacNabb and Boersma, 1993; Dias Junior, 1994; Dias Junior and Pierce, 1996ab; Canarache et al., 2000). These curves describe the relationship between the logarithm of the applied pressure and bulk density or void ratio (Casagrande, 1936; Leonards, 1962; Holtz and Kovacs, 1981). The precompression stress divides the soil compression curves into a region of small, elastic and recoverable deformation (secondary compression curve) that defines soil management history and a region of plastic and unrecoverable deformation (virgin compression curve) (Holtz and Kovacs, 1981; Jamiolkowski et al., 1985; Gupta et al, 1989; Lebert and Horn, 1991; Dias Junior and Pierce, 1995; Canarache et al., 2000) (Figure 1). Thus the development of this methodology was based on the soil compression curve.

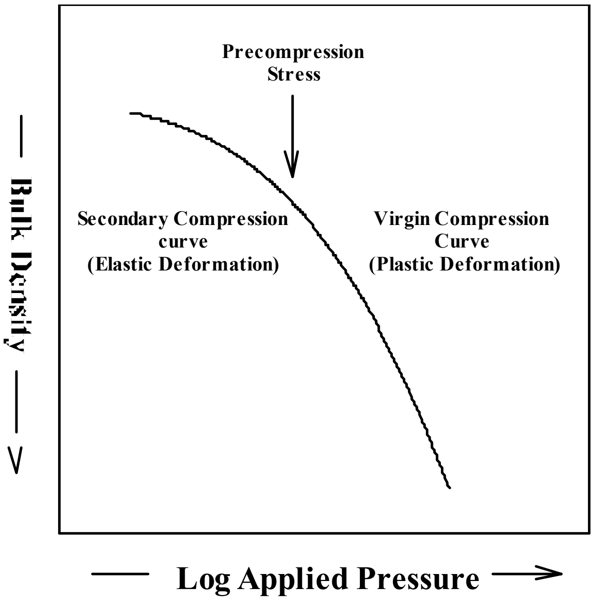

Figure 1. Soil compression curve. Source: Dias Junior (1994).

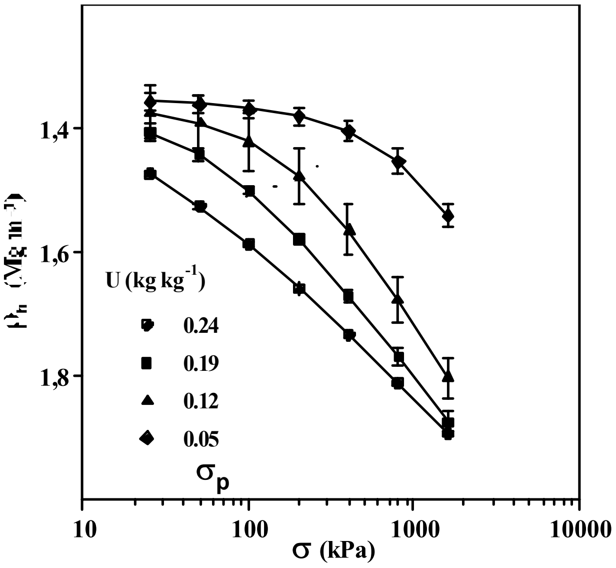

Figure 2. Soil compression curves at different moisture content (U). The dotted line indicates the precompression stress. Source: Dias Junior (1994).

The shape of the soil compression curves varies with moisture content (Figure 2) and therefore, affecting the secondary and the virgin compression curves (Dias Junior, 1994; Dias Junior and Pierce, 1995) and the precompression stress (figure 2).

Considering the changes in the shape of the soil compression curves, Dias Junior (1994) suggested a soil compressibility model based on the soil compression curves, obtained for different moisture conditions. This model consists of two parts (Figure 3):

a) Soil management model (Figure 3a) that may be used to estimate the maximum pressure that can be applied to the soil in order to avoid structure degradation and also may be used to estimate the pressure that roots may need to do in order to overcome soil strength. This model takes the general form: $\sigma_p = 10^{(a + b\,U)}$, where: σ_p = precompression stress (kPa), U = moisture content (kg kg^{-1}), and "a" and "b" are fitted parameters.

b) Virgin compression model (Figure 3b) that may be used to estimate the deformations that could occur when pressure greater than the precompression stress is applied to the soil. This model takes the general form: $\rho_{bfinal} = \rho_{b\sigma p} + m \log (\sigma_{final} / \sigma_p)$ where ρ_{bfinal} = final bulk density (Mg m^{-3}), $\rho_{b\sigma p}$ = bulk density at the precompression stress (Mg m^{-3}), m = compression index (Mg m^{-3}), σ = applied pressure (kPa) and σ_p = precompression stress (kPa).

The next step of the development of this methodology was based on how to determine precompression stress in a fast a simple way. In order to do that it was found in the literature that some of the methods used to estimate precompression stress are graphical procedure (Casagrande, 1936; Burmister, 1951; Schmertmann, 1955). Additional methods have been used to estimate precompression stress, primarily involving regression (Sällfors, 1975; Culley and Larson, 1987; Jose et al., 1989; Lebert and Horn, 1991) and prediction from undrained shear strength and effective vertical overburden pressure (Anderson and Lukas, 1981). None of these estimation techniques is considered a standard technique. Although the method suggested by Casagrande (1936) is one of the most used in civil engineering, this method is based on the choice of the point in the compression curve with minimum radius of curvature. It has been shown that as soil sample disturbance increases, the selection of this point is increasingly more difficult and the precompression stress will be lower than those obtained for undisturbed soil samples (Schmertmann, 1955; Brumund et al., 1976; Holtz and Kovacs, 1981). Also, when using undisturbed soil samples at high moisture content, the selection of the point of minimum radius also can be difficult because the compression curve is nearly linear (Dias Junior, 1994).

Therefore, Dias Junior and Pierce (1995) evaluated a number of procedures for estimation of the precompression stress from uniaxial compression test. The procedures were evaluated against the Casagrande graphical estimation procedure and published values of precompression stress. The procedure that best met the performance criteria for prediction of precompression stress was programmed into standard computer spreadsheet software (Table 1 and Figure 4).

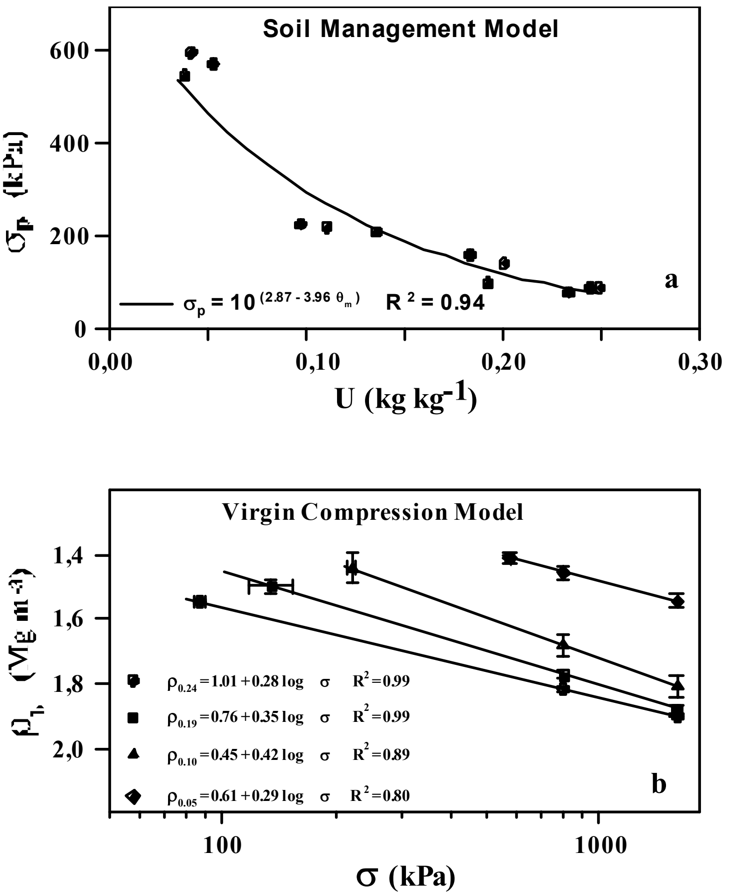

Figure 3. The soil management model (a) expressing precompression stress (σ_p) as a function of moisture content (U); and the virgin compression model (b) expressing bulk density (ρ_b) as a function of applied stress (σ). Source: Dias Junior (1994) and Dias Junior and Pierce (1996).

Table 1. Spreadsheet for determination of the precompression stress (σ_p) from soil compression curves. Source: Dias Junior and Pierce (1995).

Stress	Log Stress	ρ_b	ρ_b vcc	ρ_b reg
25	1.3979	1.3905	1.2897	1.3845
50	1.6960	1.4444	1.3825	1.4502
100	2.0000	1.5097	1.5160	1.5160
200	2.3010	1.5878	1.5681	1.5847
400	2.6021	1.6712	1.6609	1.6474
800	2.9031	1.7537	1.7537	1.7131
1600	3.2041	1.8465	1.8465	
Method 1 (Suction < 100 kPa)			Method 3 (Suction > 100 kPa)	
σ_p =	151 kPa		σ_p =	238 kPa
ρ_b =	1,53 Mg m^{-3}		ρ_b =	1,61 Mg m^{-3}

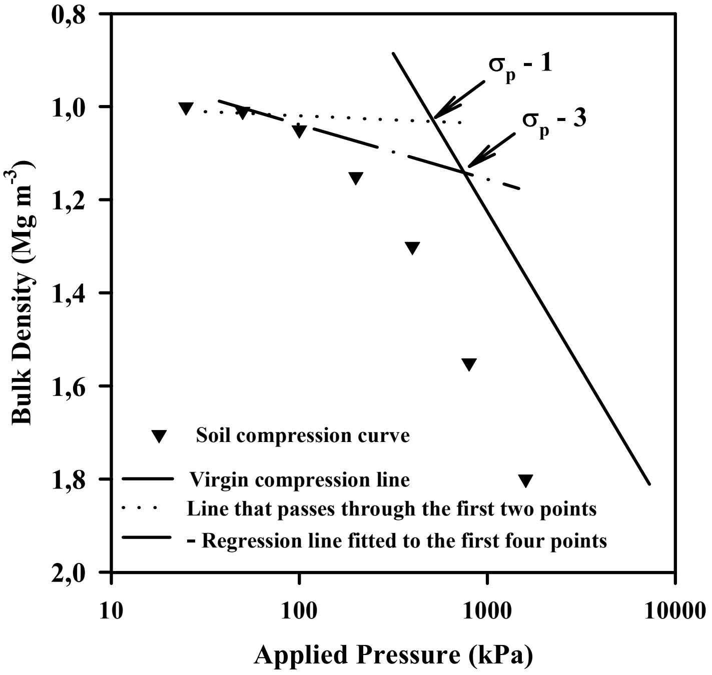

Figure 4. Computer screen of the soil compression curve showing the precompression stress(σ_p) obtained using method 1 and method 3. Source: Dias Junior (1994).

TRAFFIC EFFECT ON THE PRECONSOLIDATION PRESSURE OF TROPICAL SOILS

Evaluation of the susceptibility of soil management systems to compaction

Kondo and Dias Junior (1997 and 1999) evaluated the changes in the precompression stress as a function of the moisture content of a Red-Yellow Latosol (Oxisol) under annual crop, cultivated pasture and native forest. The undisturbed soil samples were taken randomly at 0-3 cm depth. According to figure 5, it was observed a shifting for the region of lower pressure of the curve of precompression stress as a function of moisture content for the annual crop in relation of the curve of native forest, which is due to the destruction of soil structure by the tillage tools, suggesting therefore, greater soil susceptibility to compaction of the soil under annual crop. For the cultivated pasture, the precompression stress was greater than for the annual crop and the native forest, evidencing the influence of the trampling of the cattle on the compaction of the soil surface.

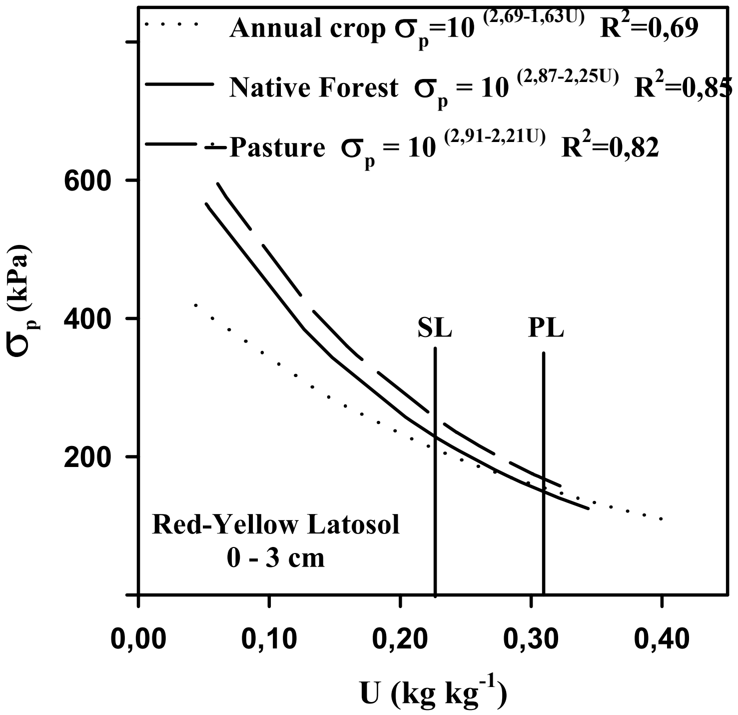

Figure 5. Relationship between precompression stress (σ_p) and moisture content (U) for a Red-Yellow Latosol at 0-3 cm depth, for annual crop, native forest and cultivated pasture. SL = Shrinkage limit, PL = Plastic limit. Source: Kondo and Dias Junior (1997 and 1999).

In order to verify the possible alteration of the soil structure caused by the *Eucalyptus* plantation at 0-3 cm and 35-38 cm depth of a Yellow Podzolic (Acrudoxic Kandiudult), Dias Junior et al., (1999), compared the curves of precompression stress as a function of moisture content for the conditions of native forest and eucalyptus plantation (Figure 6). The curves of precompression stress as a function of moisture content at 0-3 cm depth were statistically different and showed smaller precompression stress than the native forest for any moisture condition. This fact evidenced an alleviation of the natural soil strength by the tillage operations. There were no statistically differences in the precompression stress at 35-38 cm depth for these two conditions, showing that the soil tillage operations did not alter the soil structure at this depth.

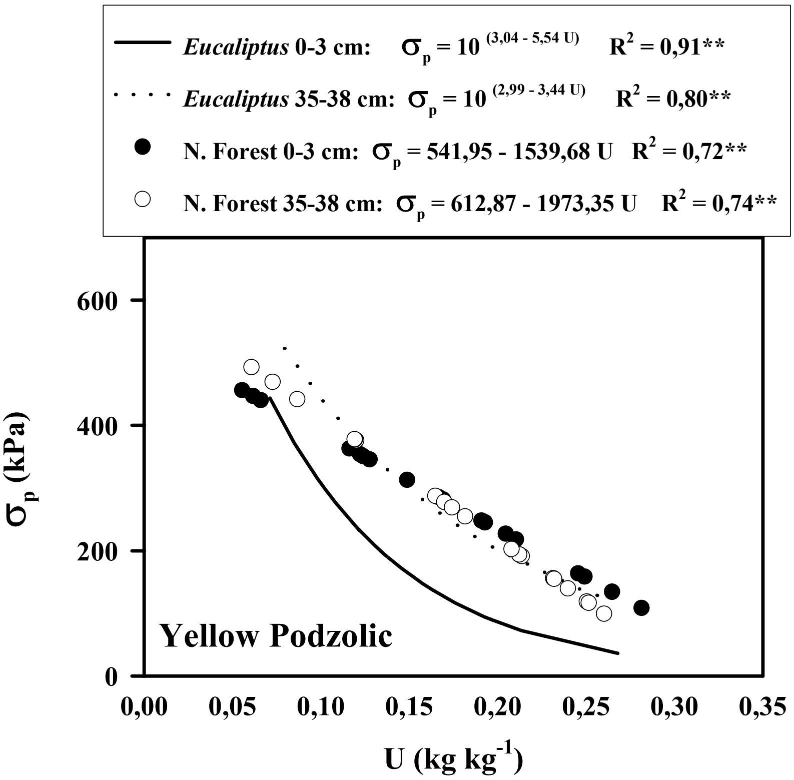

Figure 6. Relationship between the precompression stress (σ_p) and moisture content (U) for the Yellow Podzolic for the 0-3 and 35-38 cm depth for native forest and *Eucalyptus* plantation. Source: Dias Junior et al. (1999).

Evaluation of the susceptibility of soil classes/horizons to compaction

The figures 7 and 8 show the curves of precompression stress as a function of moisture content for a Yellow Podzolic (Acrudoxic Kandiudult) and for a Plinthosol (Acrudoxic Plintic Kandiudult) at 0-3 and 35-38 cm depth. For the 0-3 cm depth (Figure 7), the curves of the two soils were statistically different and the Plinthosol showed values of precompression stress significantly greater than the Yellow Podzolic, for any value of moisture content. It is expect, therefore, that at 0-3 cm depth, the Yellow Podzolic should be more susceptible to soil compaction than Plinthosol. For the 35-38 cm depth, the curves of precompression stress as a function of moisture content were not statistically different (Dias Junior et al., 1999).

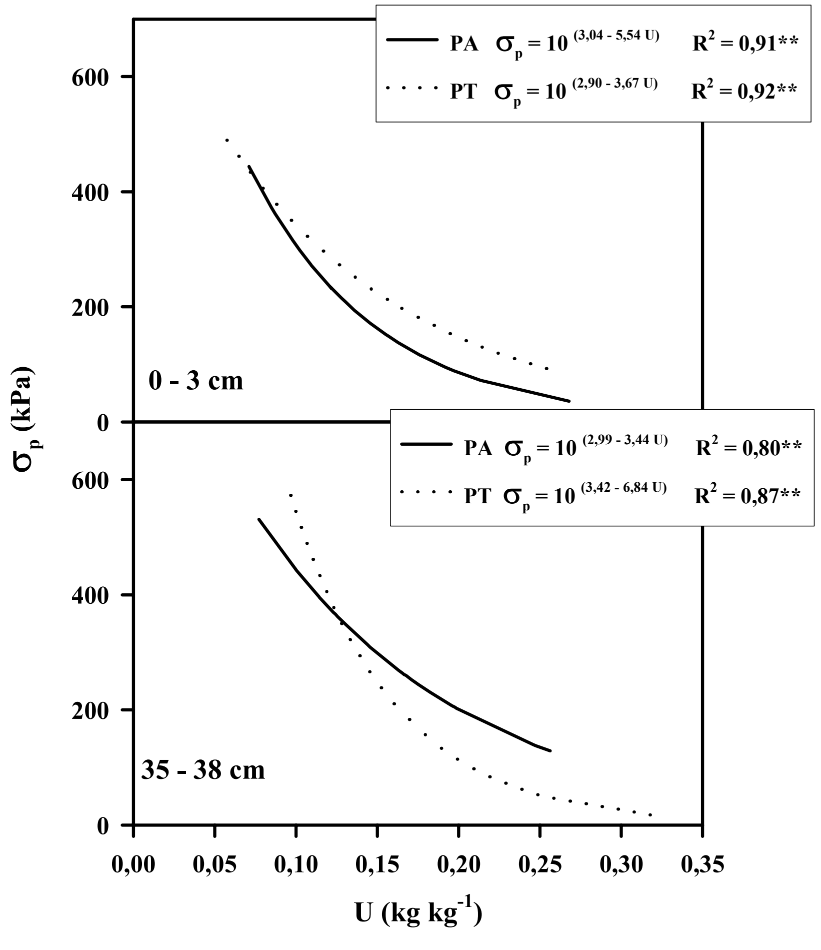

Figure 7. Relationship between precompression stress (σ_p) and moisture content (U), for the Yellow Podzolic (PA) and Plinthosol (PT) for the 0-3 and 35-38 cm depth. Source: Dias Junior et al. (1999).

The curves of precompression stress as a function of moisture content at 0-3 cm depth were statistically different from those at 35-38 cm for the Yellow Podzolic and for the Plinthosol (Figure 8). The depth 35-38 for a Yellow Podzolic, showed greater value of precompression stress than at 0-3 cm depth, and for the Plinthosol it was observed only when the moisture content was smaller than 0,14 kg kg^{-1}. These differences might be related with the soil formation processes. Considering those results, it is expected that at 0-3 cm depth of these soils should be more susceptible to soil compaction than at 35-38 cm depth, except for the Plinthosol at moisture content greater than 0,14 kg kg^{-1}. (Dias Junior et al., 1999).

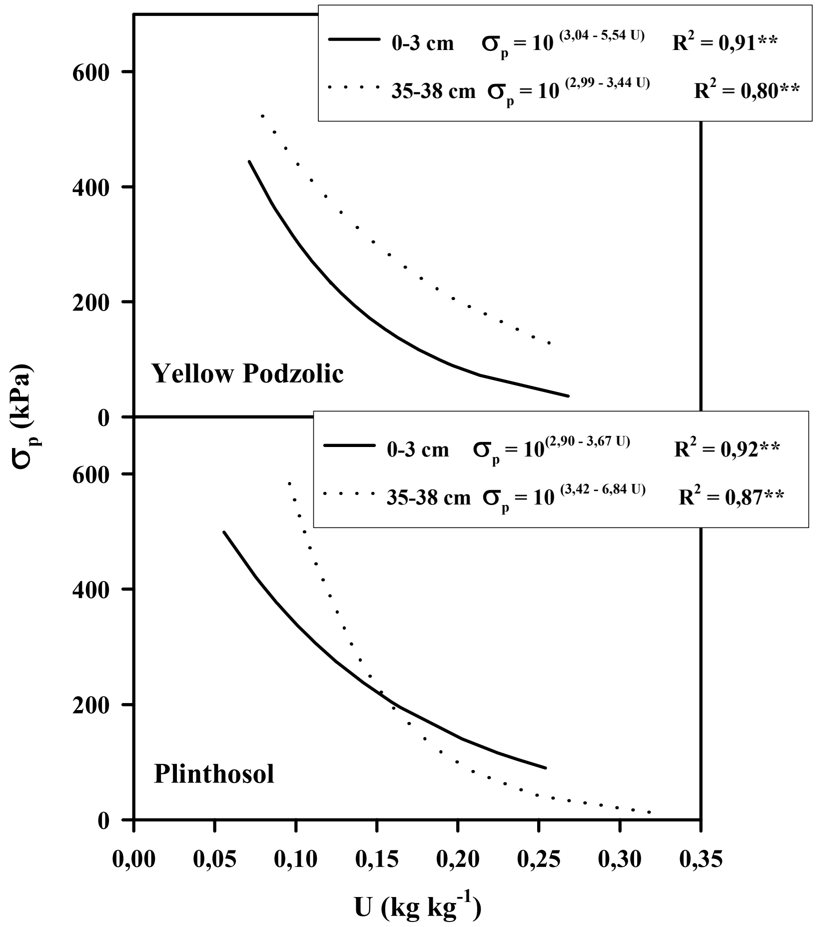

Figure 8. Relationship between precompression stress (σ_p) and moisture content (U) at 0-3 and 35-38 cm depth of the Yellow Podzolic and Plinthosol. Source: Dias Junior et al. (1999).

For a Yellow Latosol (Oxisol), it was observed that at 15-18 cm depth, was statistically different from the 0-3 cm depth (Figure 9), showing greater values of precompression stress than this depth and therefore higher resistance to soil compaction.

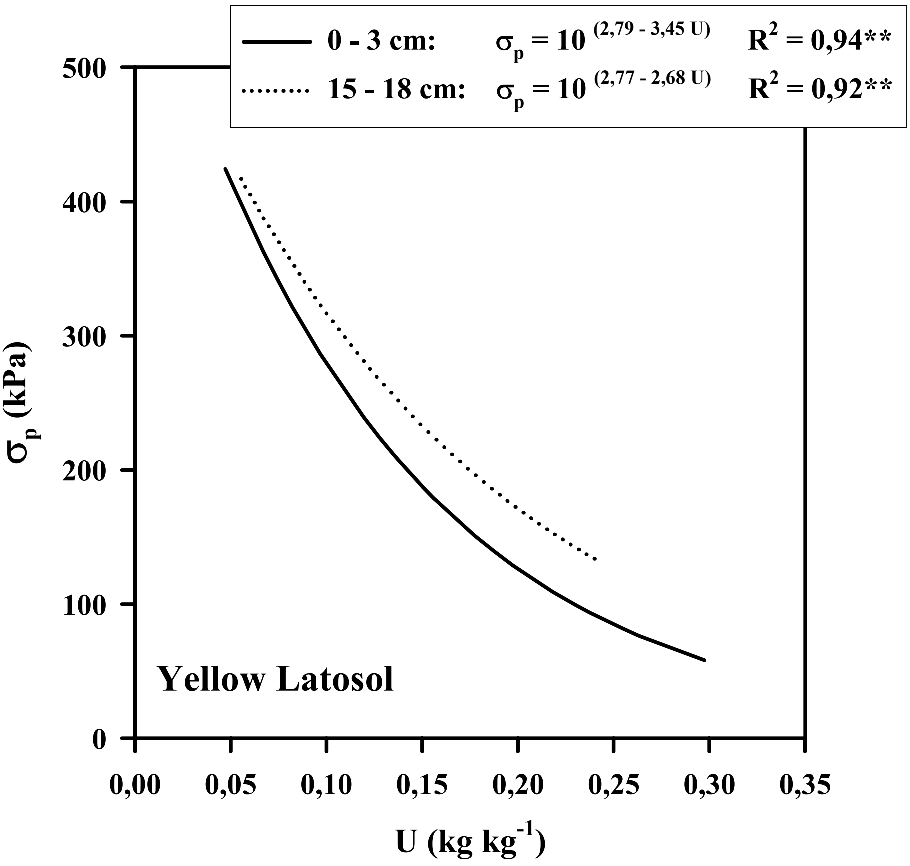

Figure 9. Relationship between the precompression stress (σ_p) and moisture content (U) for the 0-3 and 15-18 cm depth of Yellow Latosol. Source: Dias Junior (2000).

In summary, one might expect that soil with larger values of precompression stress should have large values of load support capacity and therefore, and larger resistance to soil compaction. However, one might consider that root system developing in a place with large precompression stress, should experiment higher soil mechanics resistance than those that are growing in place of lower precompression stress. Thus, the understanding of changes in precompression stress with the soil management is important.

Evaluation of the susceptibility of soil under *Eucalyptus* plantation

Considering that in agriculture, the application of pressures larger than the largest pressure applied previously to the soil should be avoided in order to avoid additional soil compaction (Gupta et al., 1989; Lebert and Horn, 1991) and that the precompression stress is an indicative of the maximum applied pressure to the soil in the past (Holtz and Kovacs, 1981; Dias Junior, 1994) figure 10, was then divided into three regions to evaluate the traffic effects and the natural alleviation of the precompression stress. The considered regions (Figure 10) are: a) the region where the precompression stress determined after the traffic (σ_{pt}) are larger than the maximum precompression stress estimated with the equation of the Confidence Interval at 95% (σ_p maximum estimated), being considered as the region where the soil structure degradation had already happened; b) the region where precompression stress determined after the traffic (σ_{pt}) are larger than the precompression stress estimated with the equation of the relationship between σ_p and U(σ_p) and smaller than the maximum precompression stress estimated with the equation of the Confidence Interval at 95% (σ_p maximum estimated), being considered as the region where there is a tendency of soil structure degradation to happen and c) a region where the precompression stress determined after the traffic (σ_{pt}) are smaller than the precompression stress estimated with the equation of the relationship between σ_p and U (σ_p), being considered as the region where there is no soil structure degradation.

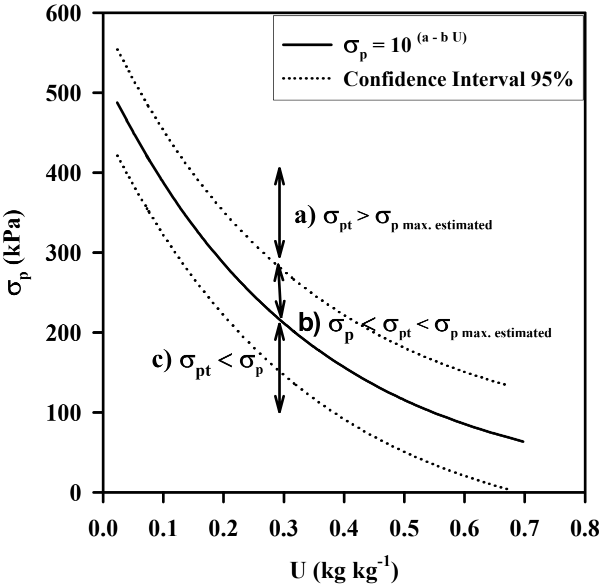

Figure 10. Relationship between precompression stress (σ_p) and moisture content (U). (Source: Dias Junior, 2002).

With the standardization of specific legislation regarding the exploration of natural resources, the companies involved in this type of activity are alert about the problems that their mechanical activities can cause to the soil structure. Therefore, they are interested in obtain answer to questions such as: a) Any increase in soil bulk density values means additional soil compaction? b) Which soil class is more susceptible to soil compaction? c) Which harvest machinery can cause more soil compaction? d) What is the influence of harvest operations in A and B-horizons? Thus, the studies conducted in this area should consider as an attempt to find some answer for those question, in a way to contribute with the sustainability of the areas of *Eucalyptus* exploration.

One of the studies conducted, as an attempting to answer those questions was done by Dias Junior et al., (1999). The objectives of this study were: a) to suggest and monitor precompression stress as a quantitative indicator of the structure sustainability of the soils cultivated with *Eucalyptus*; b) to propose a model of structure sustainability of the soils cultivated with *Eucalyptus*, based on precompression stress and moisture content; c) to determine the effect of harvest machinery on soil structure, through these models; d) to monitor precompression stress every two years in order to verify if some alleviation of the structure degradation is occurring, due to the biological activity or due to drying and wetting cycles. This study was conducted in a Yellow Podzolic (Acrudoxic Kandiudult) and in a Plinthosol (Acrudoxic Plintic Kandiudult), under native forest and *Eucalyptus.* In each soil class, sampling consisted of two stages: before and after the mechanized harvest operations. In each stage, nine undisturbed soil samples were collected at 0-3 cm and at 35-38 cm depth, using 3 replications, with a total of 54 undisturbed soil samples. The undisturbed soil samples were used in the uniaxial compression tests. The soils samples taken before the crop operations were used to obtain the relationship between precompression stress and moisture content and the confidence interval at 95%. The relationship between precompression stress and moisture content will be called from now on, structure sustainability model. The soils samples taken after the mechanized harvest were done after the operation with Feller-Büncher, Harvester and Forwarder. From these soil samples precompression stress were obtained at the natural moisture content and these values were plotted in the structure sustainability model as an attempt to find a methodology that may be became used to quantify the effect of harvest operations in the soil structure (Figures 11 to 14).

In figures 11 to 14, it is observed that the Feller-Büncher did not cause structure degradation in both depth and soil classes. In figures 11 to 14 it is observed that only for the Yellow Podzolic at 0-3 cm depth, the Harvester caused some structure degradation (Figure 11). The Forwarder, however, caused structure degradation in both soil classes at 0-3 cm depth, as showing in figures 11 and 13. For the 35-38 cm depth, the Forwarder also did not caused structure degradation.

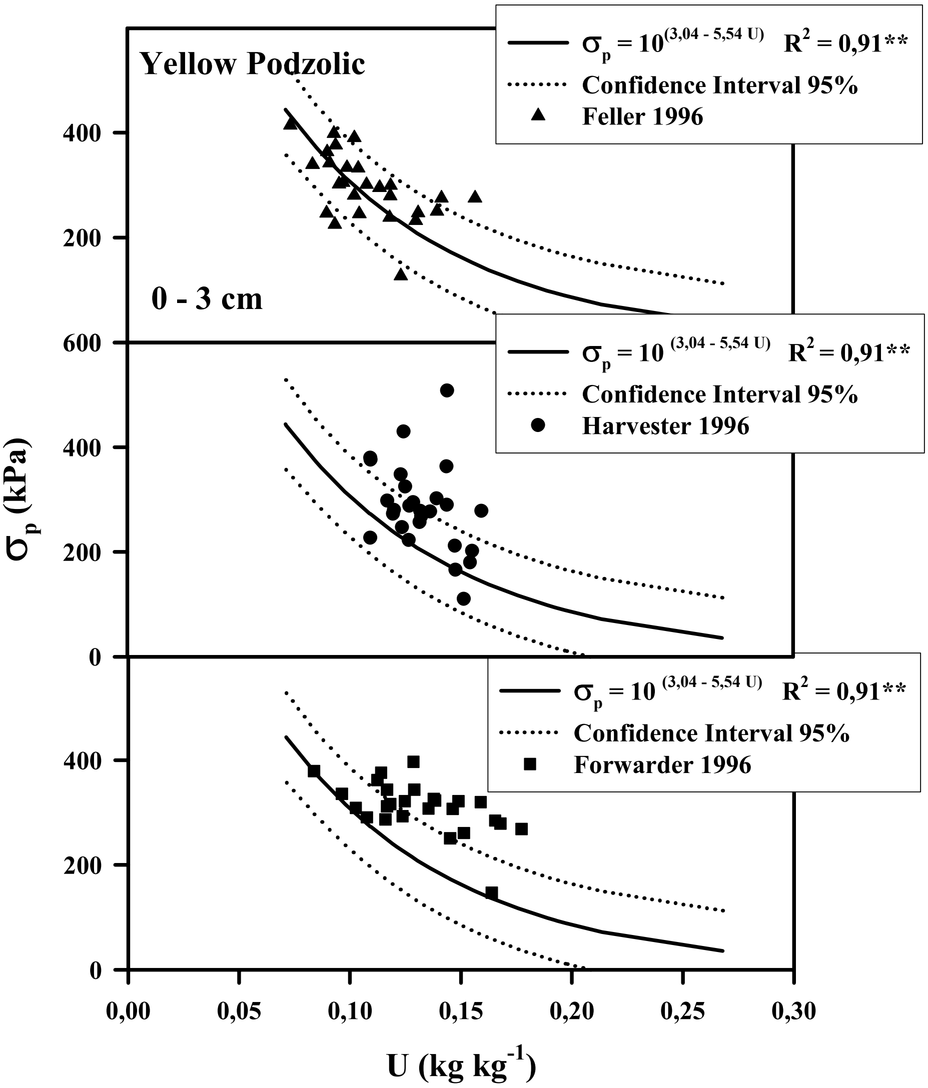

Figure 11. Relationship between the precompression stress (σ_p) and moisture content (U) for Yellow Podzolic after Feller-Büncher, Harvester and Forwarder operations, on the 0-3 cm depth. Source: Dias Junior et al. (1999).

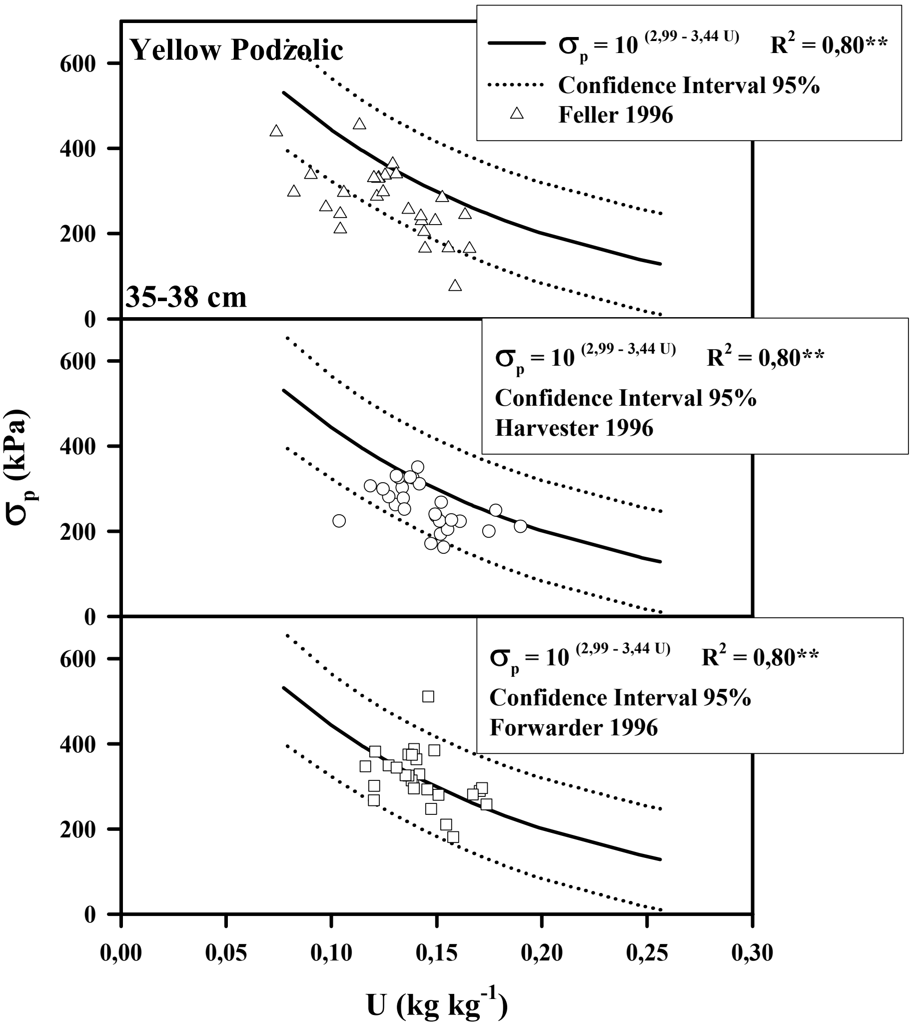

Figure 12. Relationship between the precompression stress (σ_p) and moisture content (U) for Yellow Podzolic after Feller-Büncher, Harvester and Forwarder operations, on the 35-38 cm depth. Source: Dias Junior et al. (1999).

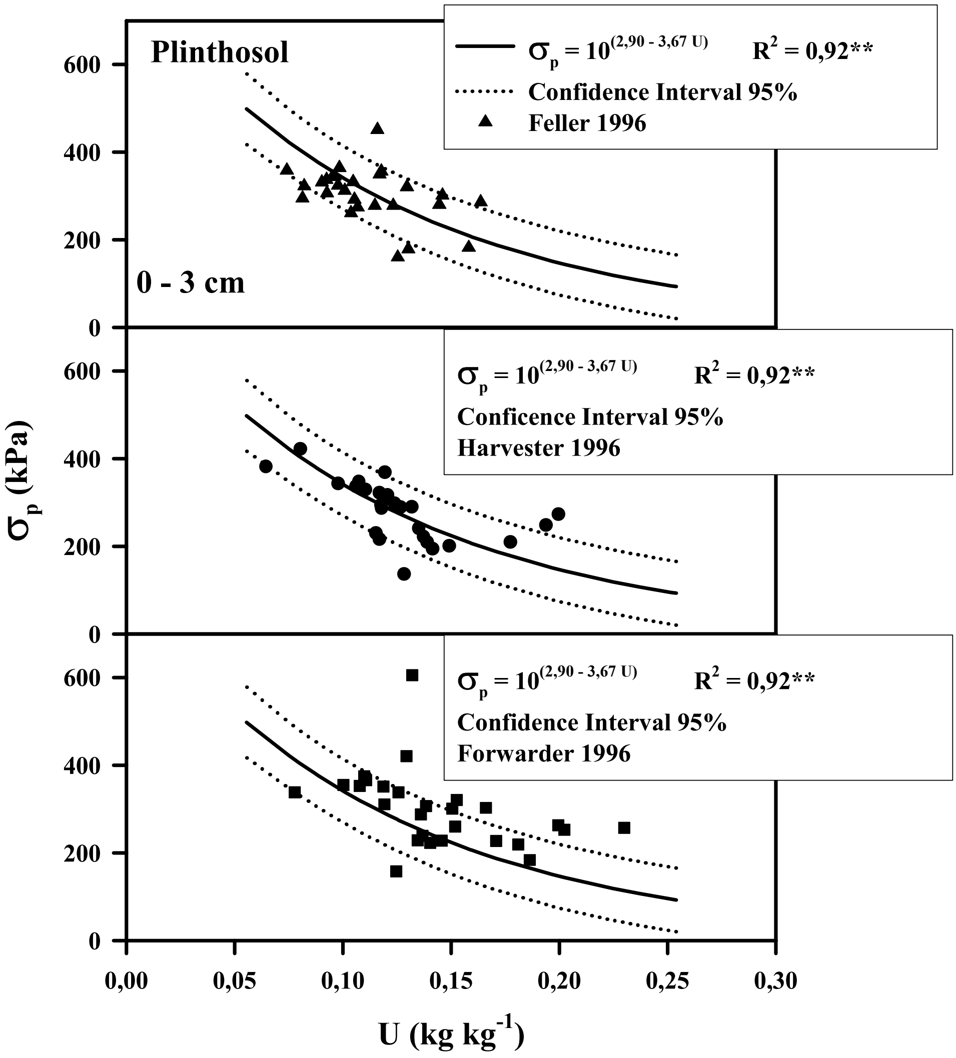

Figure 13. Relationship between the precompression stress (σ_p) and moisture content (U) for Plinthosol after Feller-Büncher, Harvester and Forwarder operations, on the 0-3 cm depth. Source: Dias Junior et al. (1999).

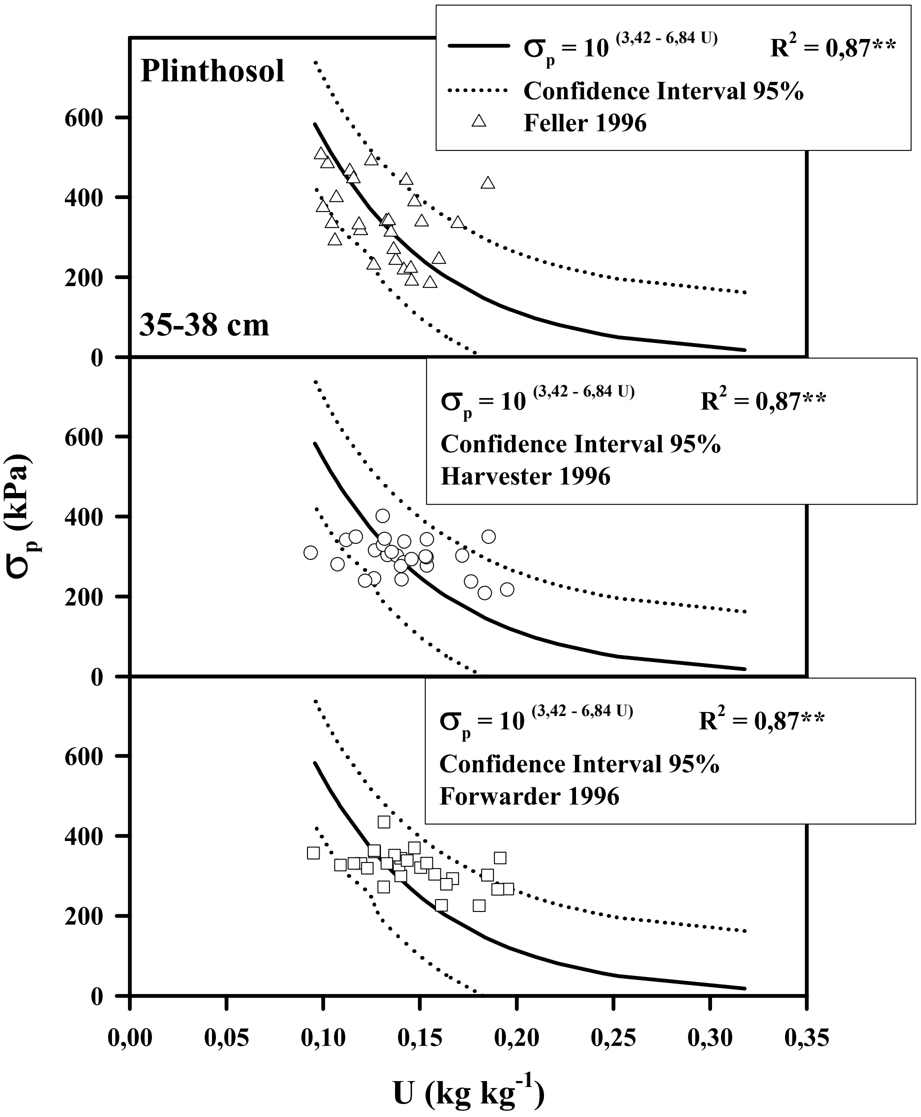

Figure 14. Relationship between the precompression stress (σ_p) and moisture content (U) for Plinthosol after Feller-Büncher, Harvester and Forwarder operations, on the 35-38 cm depth. Source: Dias Junior et al. (1999).

To quantify the impact on the soil structure caused by the harvest operations of the eucalyptus plantation, done by two sets of machines, one Feller Büncher (2618 crawler) and Skidder (460 with tires 30.5L.32) and the other Harvester (1270 with tires 700 x 26.5) and Forwarder (1710 with tires 750 x 26.5) in the dry and rainy seasons, a experiment was conducted in a Red Yellow Latosol (Oxisol) at 0.10-0.125 m depth. The results of this experiment are showed in table 2.

Table 2. Precompression stress induced by Feller Büncher (2618 de crawler) and Skidder (460 with tires 30.5L.32), and Harvester (1270 tires 700x26.5) and Forwarder (1710 with tires 750x26.5) in a Red Yellow Latosol, at 0.10-0.125 m depth. (Source: Dias Junior, 2002b)

Harvest machines	σ_{pt}[1] > $\sigma_{p\ max\ est}$[2]		
	Dry season	Rainy season	Δ (%)
Feller Büncher and Skidder	5	15	200
Harvester and Forwarder	8	31	287
Δ (%)	60	106	

1 – Pressure applied by the harvest machines, 2 – Precompression stress estimated with the equation of the confidence interval at 95%.

Table 2, shows that the harvest operations performed with Harvester and Forwarder in the dry season, increased the precompression stress values in 60% in relation to the precompression stress induced by Feller Büncher and Skidder and in the rainy season this increase was 106%. In addition, the precompression stress induced by Feller Büncher and Skidder, and Harvester and Forwarder increased in 200% and 287%, respectively, when the harvest operations were performed in the rainy season. Although, the operations performed with Harvester and Forwarder caused more soil structure degradation, one might consider that the traffic done with Harvester and Forwarder is located, while the traffic done with Feller Büncher and Skidder is random and could consequently, disseminate the compaction in the whole area.

Assessment of the natural alleviation of the precompression stress

To access the natural alleviation of the precompression stress due to the drying and wetting cycle, as well as, due to the biological activity, the criteria suggested in figure 10, was considered and the precompression stress as a function of moisture content were determined in 1996, 1998 and 2000 in the traffic line of the Forwarder, and plotted in figures 15 and 16 for the Yellow Podzolic at 0-3 cm depth and for the Phinthosol at 35- 38 cm depth, respectively. Figure 15 shows that at 0-3 cm depth, is occurring a decreasing in the percentage of soil samples in the region where soil structure degradation had already happened (44, 22 and 11%) and an increase in the percentage of soil samples in the region where there is no soil structure degradation (4, 26 and 56%). In figure 16, it was observed only an increase in the percentage of soil samples in the region where there is no soil structure degradation (30, 33 and 52%). Thus, it was concluded that: a) the soil compaction occurred only in the topsoil layer and it was restricted to the Harvester traffic line; b) at the end of four years, even without soil tillage, it was observed that there was a natural alleviation of the topsoil compaction due to the biological activity proportionate by the eucalyptus plantation and c) there were no indications of irreversible alterations in the soil structure at 35-38 cm depth.

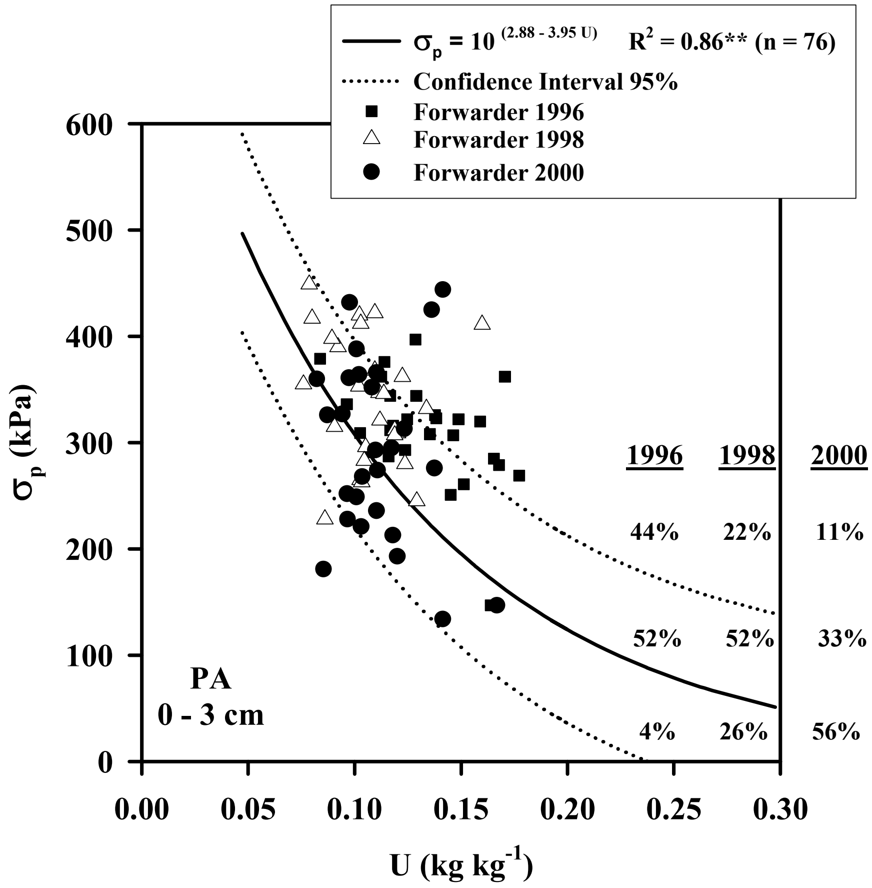

Figure 15. Relationship between precompression stress (σ_p) and moisture content (U) for a Yellow Podzolic at 0-0,03 m depth. The symbols represent the values of the precompression stress determined in soil samples collected in 1996, 1998 and 2000, in the area where the Forwarder operations occurred. (Source: Dias Junior, 2002a).

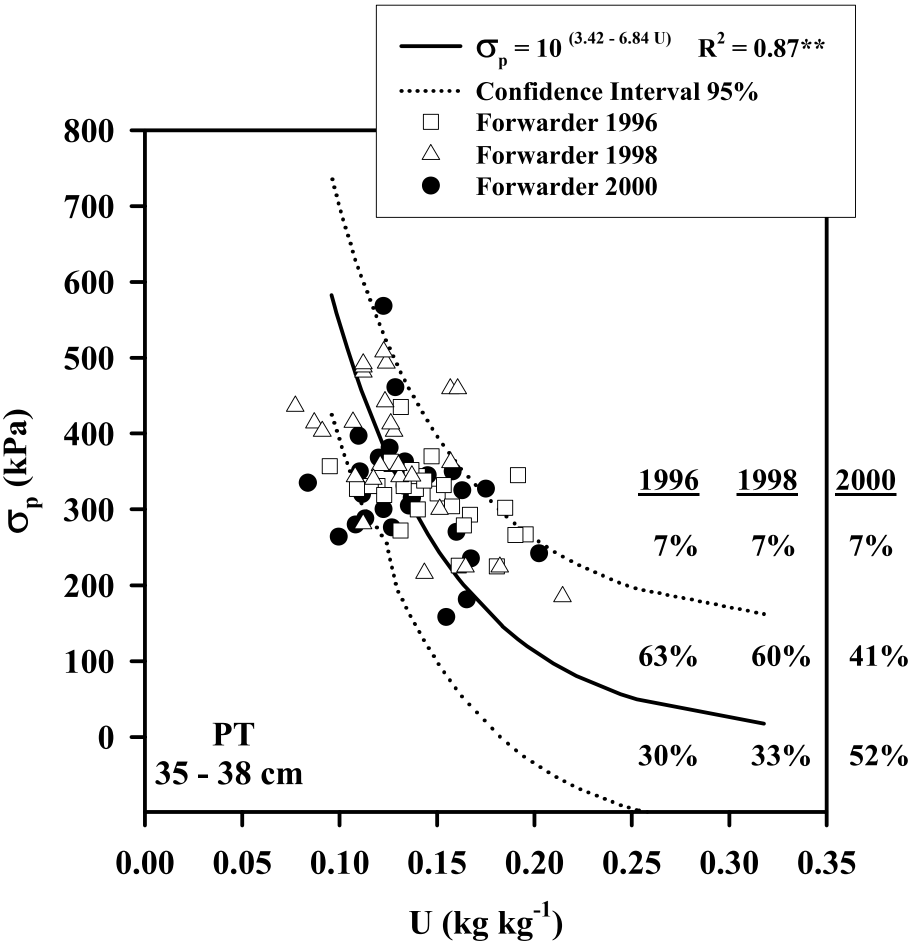

Figure 16. Relationship between precompression stress (σ_p) and moisture content (U) for a Plinthosol, at 0,35-0,38 m depth. The symbols represent the values of the precompression stress determined in soil samples collected in 1996, 1998 and 2000, in the area where the Forwarder operations occurred. (Source: Dias Junior, 2002a).

General Considerations

Several researchers have already demonstrated the causes and the effects of soil compaction. These studies showed that the soil compaction is a limiting factor in the agricultural production. The attributes of the soil conventionally monitored has not been capable to quantify the load support capacity of the soil, not allowing to foresee the levels of pressures that can be applied to the soils at different moisture conditions without additional soil compaction (structure degradation) happens. The researches done in the soil compressive behavior of some tropical soils indicate that the precompression stress may be used as an alternative measure of the load support capacity and as a quantitative indicator of the structure sustainability of the tropical soils.

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