The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2163-22

College on Soil Physics: Soil Physical Properties and Processes under Climate Change

30 August - 10 September, 2010

A SOIL MECHANICS APPROACH TO STUDY SOIL COMPACTION

Moacir de Souza Dias Junior
Department of Soil Science
Federal University of Lavras
Brazil

A SOIL MECHANICS APPROACH TO STUDY SOIL COMPACTION

Moacir de Souza Dias Junior

Department of Soil Science, Federal University of Lavras, Po Box 3037, MG, 37.200-000 Lavras, Brazil, CNPq and FAPEMIG Researcher.

msouzadj@dcs.ufla.br

ABSTRACT: One of the limitations for sustainable agriculture development to be reached is related to the traffic of machines and vehicles, which may cause soil structure degradation. The soil structure degradation can occur due to the fact that at the moment of accomplishment of the mechanized operations, there are no controls of the soil water content or of the soil load support (bearing) capacity. Thus, it becomes important to determine the soil moisture at which the soil can be submitted to mechanized operations, as well as, to quantify the damages caused to soil structure, when the applied pressures exceeds the soil load support (bearing) capacity. This chapter presents an application of the relationship between precompression stress and volumetric water content (Bearing Capacity Model), to evaluate: a) the soil compressive behavior under different soil management, b) the compressive behavior of the different soil classes and horizons and c) the compressive behavior of forest soils. In addition, a criterion to assess the natural alleviation of the soil compaction based on precompression stress is presented. The results of this study indicate that the use of the bearing capacity model, and the precompression stress determined after the traffic, allowed to quantify the compressive behavior of the soil and the effects of the

mechanized operations on the soil structure. Therefore, it is believed that the precompression stress may be used as an auxiliary criterion in planning the mechanized operations in order to avoid soil structure degradation.

Key words: Structure degradation, soil compaction, traffic, and precompression stress.

INTRODUCTION

The external forces applied to the soil may cause soil deformation. The components of soil deformation are: compaction defined by divergence or volumetric strain (Horn and Rostek, 2000; Çarman, 2002), which results in changes of soil mechanics characterization and in the soil air-water relationship (Pytka, 2001) and soil shearing, a process of changing of shape at constant volume (Horn and Rostek, 2000; Pytka, 2001).

Topsoil compaction is not considered to be a serious problem, because it can be alleviated by tillage and natural process (Arvidsson, 2001; Gysi, 2001; Radford et al., 2001). However, subsoil compaction is a major concern in agriculture, mainly due to its persistence (Arvidsson, 2001). Thus, the intensive use of the soil without moisture control is preoccupying, due to the possibility of subsoil compaction dissemination (Pedrotti and Dias Junior, 1996) caused by the traffic of agricultural machines through the year (Hill and Meza-Montalvo, 1990; Muller et al., 1990).

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).

The soil compression curves obtained from laboratory uniaxial compression 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) and a region of plastic and unrecoverable deformation (virgin compression curve) (Holtz and Kovacs, 1981; Jamiolkowski et al., 1985; Dias Junior and Pierce, 1995; Canarache et al., 2000).

The precompression stress 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). Thus, in agriculture, application of stress greater than the precompression stress should be avoid in order to avoid unrecoverable soil deformation (Gupta et al., 1989; Lebert and Horn, 1991; Defossez and Richard, 2002). The precompression stress depends on several factors such as: changes in the total stress due to erosion and excavations, wetting and drying processes, texture, structures and soil bulk density, soil management, organic matter, chemical alterations due to the weathering, precipitations, pH, ions exchange, etc. (Casagrande, 1936; Schmertmann, 1955; Crawford, 1964; Brumund et al., 1976; Holtz and Kovacs, 1981; Horn, 1988; Jose et al., 1989; Dias Junior and Pierce, 1995; McBride and Joosse, 1996, Veenhof and McBride, 1996; Kondo and Dias Junior, 1999; Silva et al., 1999 and other).

Methods for estimation of the precompression stress are available in the literature (Casagrande, 1936; Burmister, 1951; Schmertmann, 1955; Sällfors, 1975; Anderson and Lukas, 1981; Culley and Larson, 1987; Jose et al., 1989; Lebert and Horn, 1991; Dias Junior and Pierce, 1995; Veenhof and McBride, 1996 and McBride and Joosse, 1996). Thus, the use of precompression stress in the agriculture studies is consolidated.

Considering that the precompression stress is an indication of soil strength (Arvidsson, 2001) and of the maximum stress that should be applied to a soil in order to avoid soil compaction (Gupta et al., 1989; Lebert and Horn, 1991; Defossez and Richard, 2002) and also is an indicator of soil structure sustainability (Dias Junior et al., 1999), in this chapter it is present an application of the relationship between precompression stress and volumetric water content (Bearing Capacity Model), in studies of the compressive behavior of some tropical soils.

Evaluation of the compressive behavior of the soil under different soil management

To verify the soil management effect on the soil compressive behavior, Kondo and Dias Junior (1997) and Kondo (1998) evaluated the precompression stress as a function of volumetric water content for 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 1, it was observed a shifting for the region of lower pressure of the bearing capacity model for the annual crop in relation of the model 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 cattle trampling on the compaction of the soil surface.

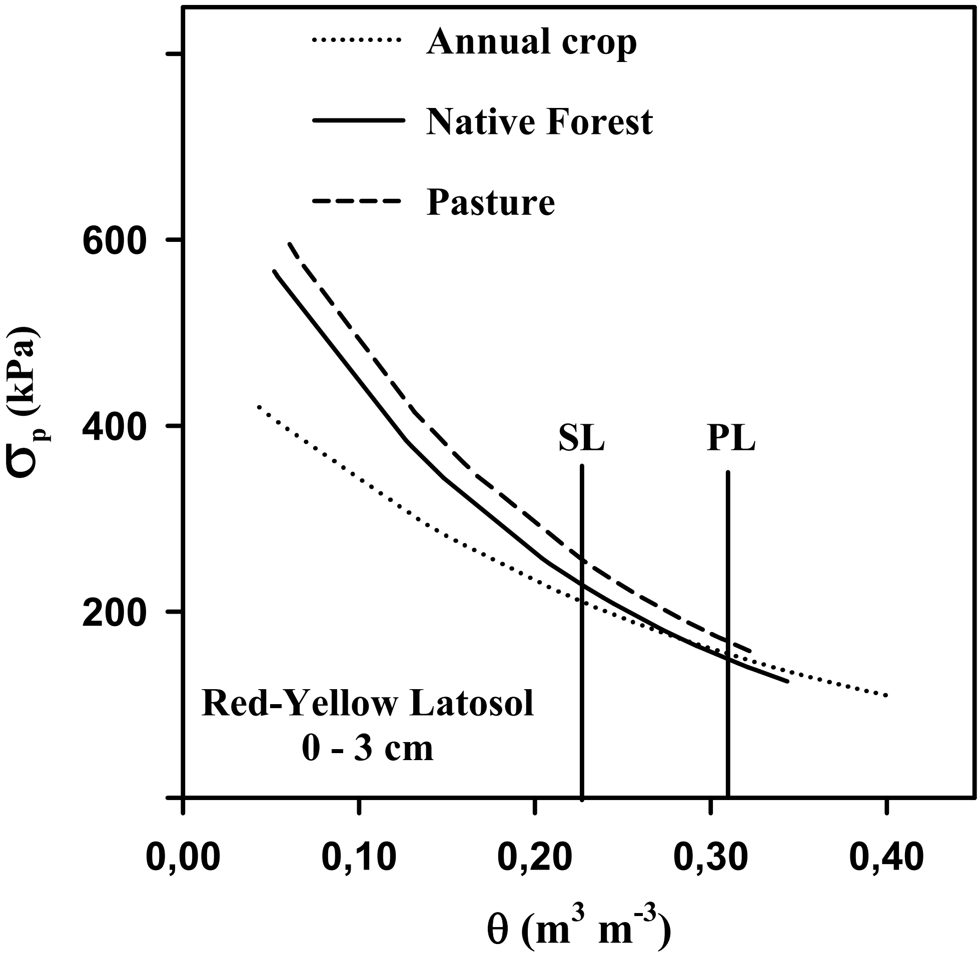

Figure 1. Bearing Capacity Model for a Red-Yellow Latosol at 0-3 cm depth, for annual crop, native forest and cultivated pasture. SL = Shrinkage limit, PL = Plastic limit. Source: Kondo and Dias Junior (1997) and Kondo (1998).

In order to verify the alterations of the soil structure caused by tillage operations in a Yellow Podzolic (Acrudoxic Kandiudult) under eucalyptus plantation at the 0-3 cm and 35-38 cm depths, Dias Junior et al., (1999), compared the Bearing Capacity Model for the conditions of native forest and eucalyptus plantation (Figure 2). The Bearing Capacity Model 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 resistance 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.

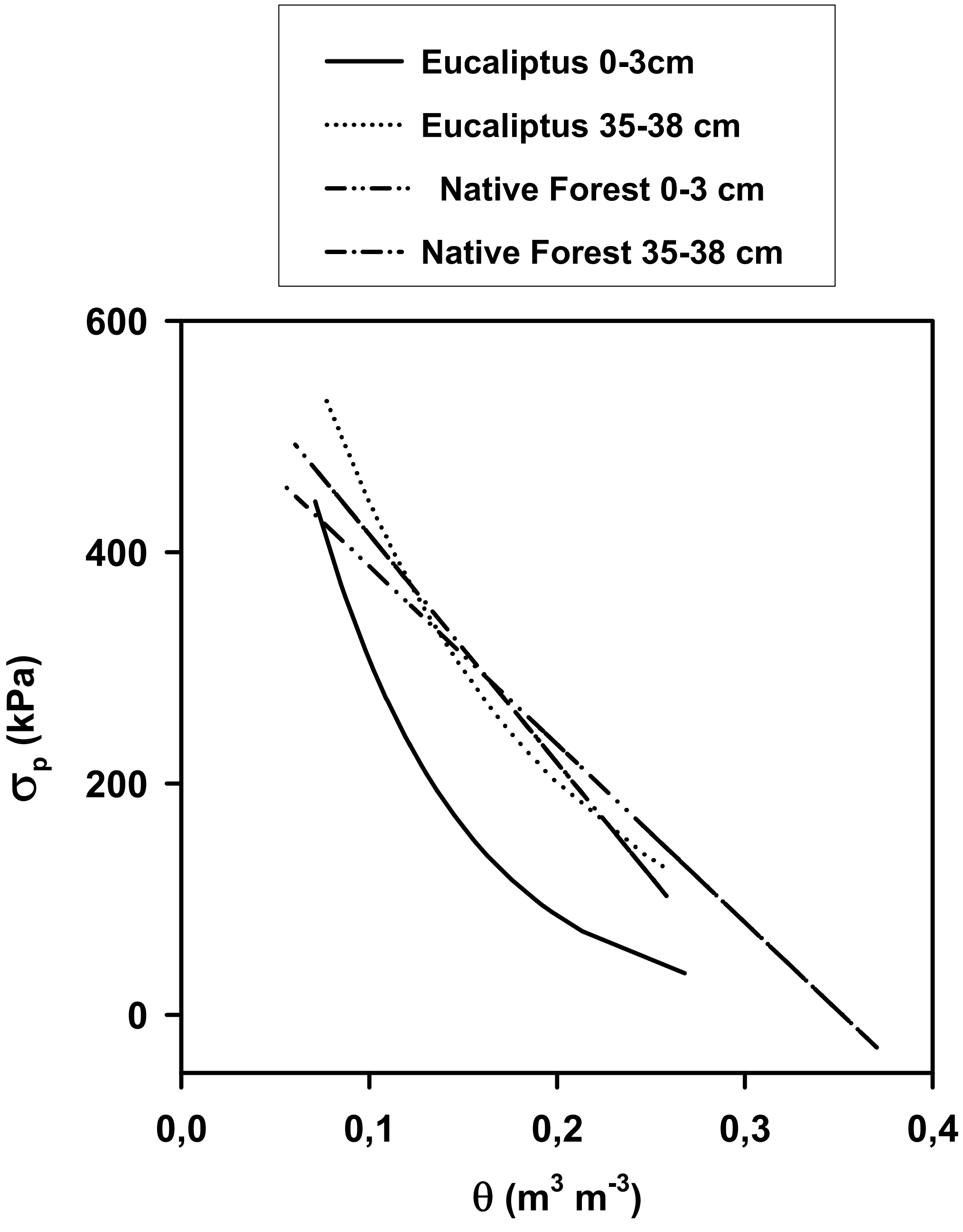

Figure 2. Bearing Capacity Model for a Yellow Podzolic at 0-3 and 35-38 cm depth, for native forest and eucalyptus plantation. Source: Dias Junior et al., (1999).

Evaluation of the compressive behavior of soil classes and horizons

Figure 3, shows the Bearing Capacity Model for a Yellow Argisol (Acrudoxic Kandiudult) and for a Plinthosol (Acrudoxic Plintic Kandiudult) at 0-3 cm depth. The models of the two soils were statistically different and the Plinthosol presented precompression stress significantly greater than the Yellow Argisol, for any value of volumetric water content. Therefore, it is expect, that the Yellow Argisol should be more susceptible to soil compaction than Plinthosol (Dias Junior et al., 1999). The understanding of the compressive behavior of the surface layer is important for the soil erosion studies, due to the fact that compaction limit water infiltration and increases soil erosion.

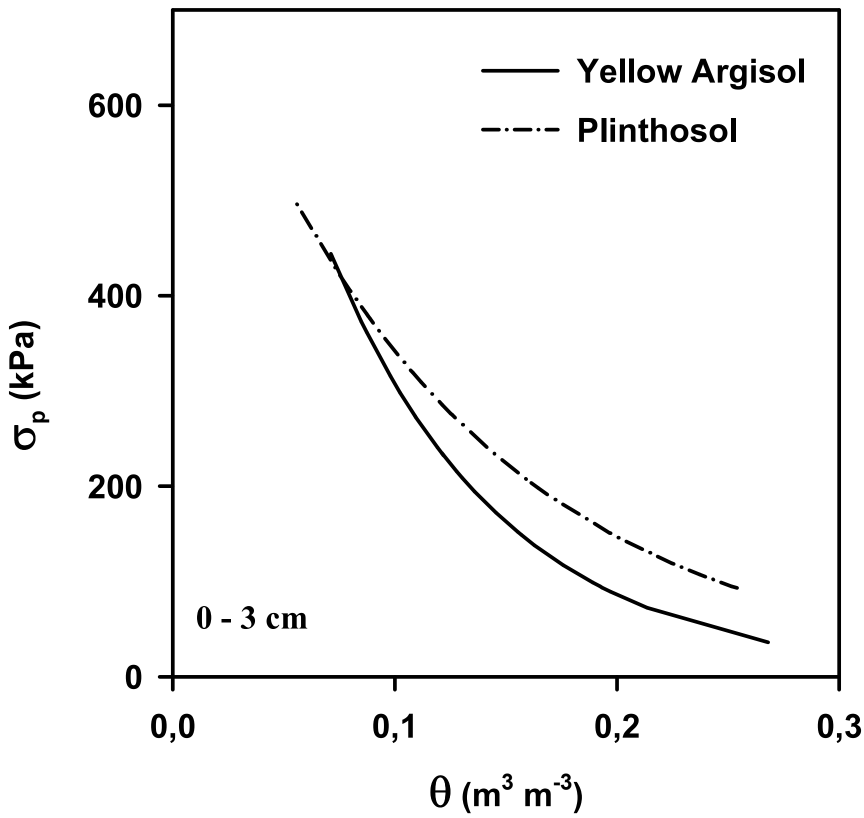

Figure 3. Bearing Capacity Model for a Yellow Argisol (PA) and Plinthosol (PT) at 0-3 cm depth. Source: Dias Junior et al., (1999).

The Bearing Capacity Model for the Yellow Argisol (Figure 4) at 0-3 cm and 35-38 cm depth were statistically different. The Yellow Argisol, at 35-38 cm depth showed greater precompression stress than the 0-3 cm depth. These differences might be related with the soil formation processes. Considering those results, it is expected that at 0-3 cm depth, these soils should be more susceptible to soil compaction than at 35-38 cm depth (Dias Junior et al., 1999).

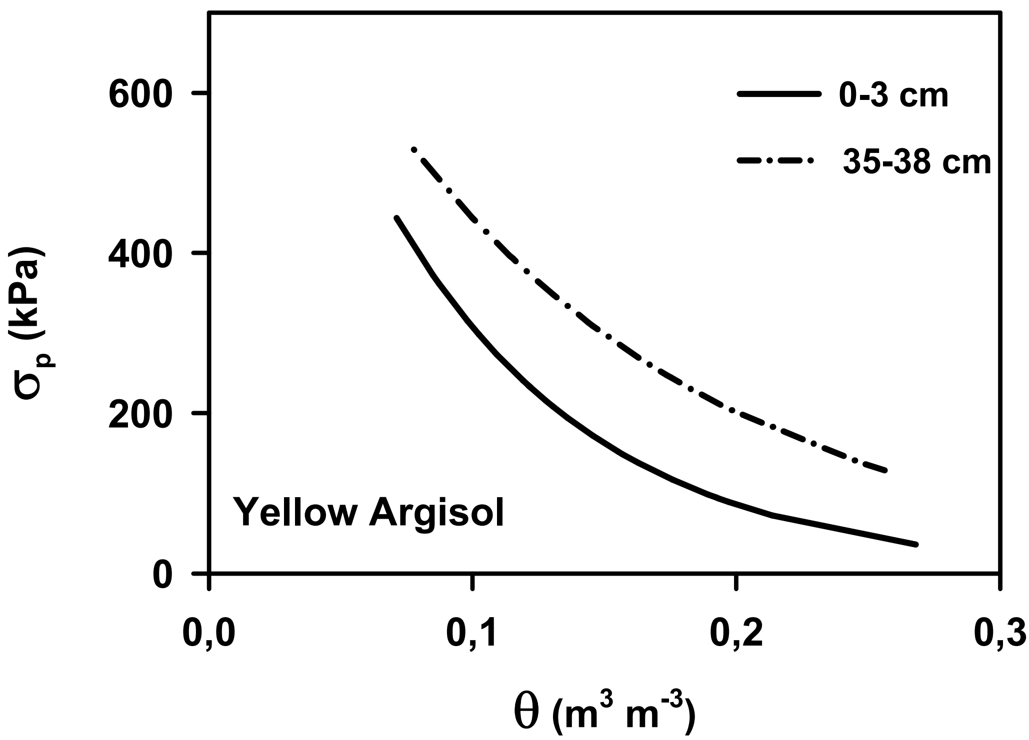

Figure 4. Bearing Capacity Model for the Yellow Argisol at 0-3 and 35-38 cm depth. Source: Dias Junior et al., (1999).

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

Evaluation of the soil compressive behavior of forest soils

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 research to identify the harvest machine that causes more soil compaction and its influence on the top and subsoil layers.

One of the studies conducted, as an attempting to identify the harvest machine effects on the soil structure was done by Dias Junior et al., (1999). This study was conducted in a Yellow Argisol (Acrudoxic Kandiudult) and in a Plinthosol (Acrudoxic Plintic Kandiudult), under native forest and eucalyptus plantation. In each soil class, the soil sampling was done before and after mechanized harvest operations. The results of this study are showed in figures 5 to 8.

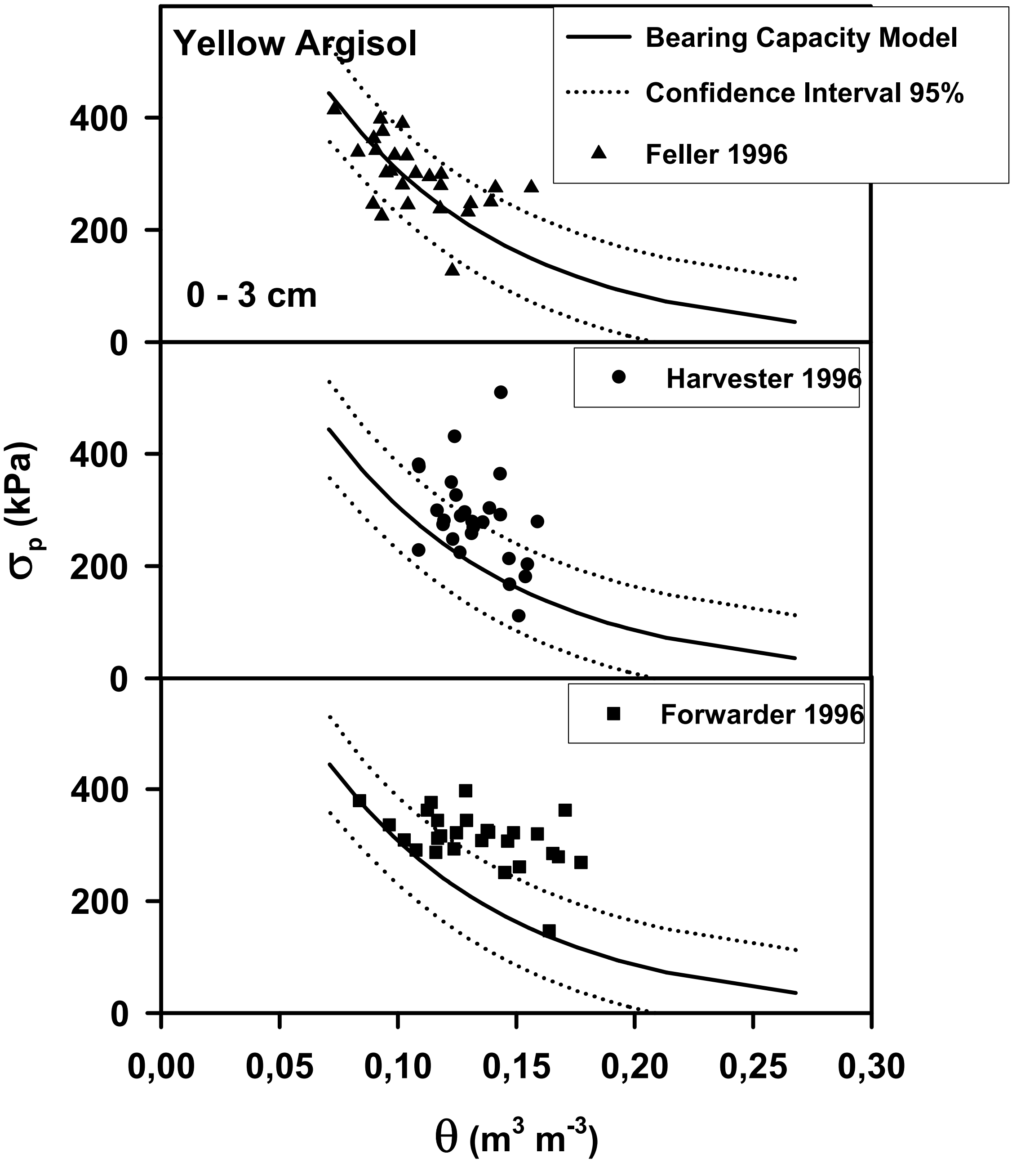

Figure 5. Bearing Capacity Model for a Yellow Argisol, after Feller-Büncher, Harvester and Forwarder operations at 0-3 cm depth. Source: Dias Junior et al., (1999).

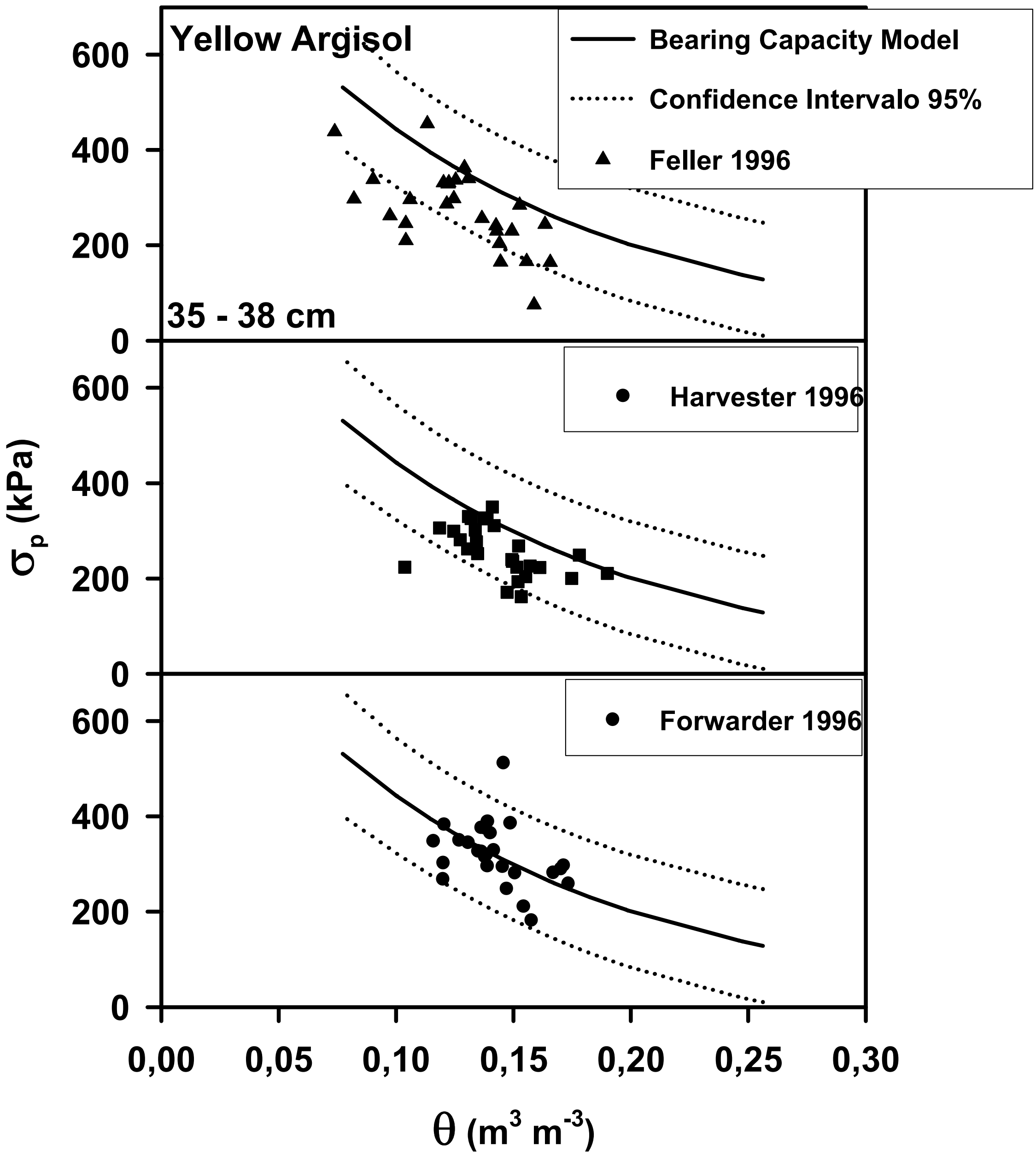

Figure 6. Bearing Capacity Model for a Yellow Argisol, after Feller-Büncher, Harvester and Forwarder operations, at 35-38 cm depth. Source: Dias Junior et al., (1999).

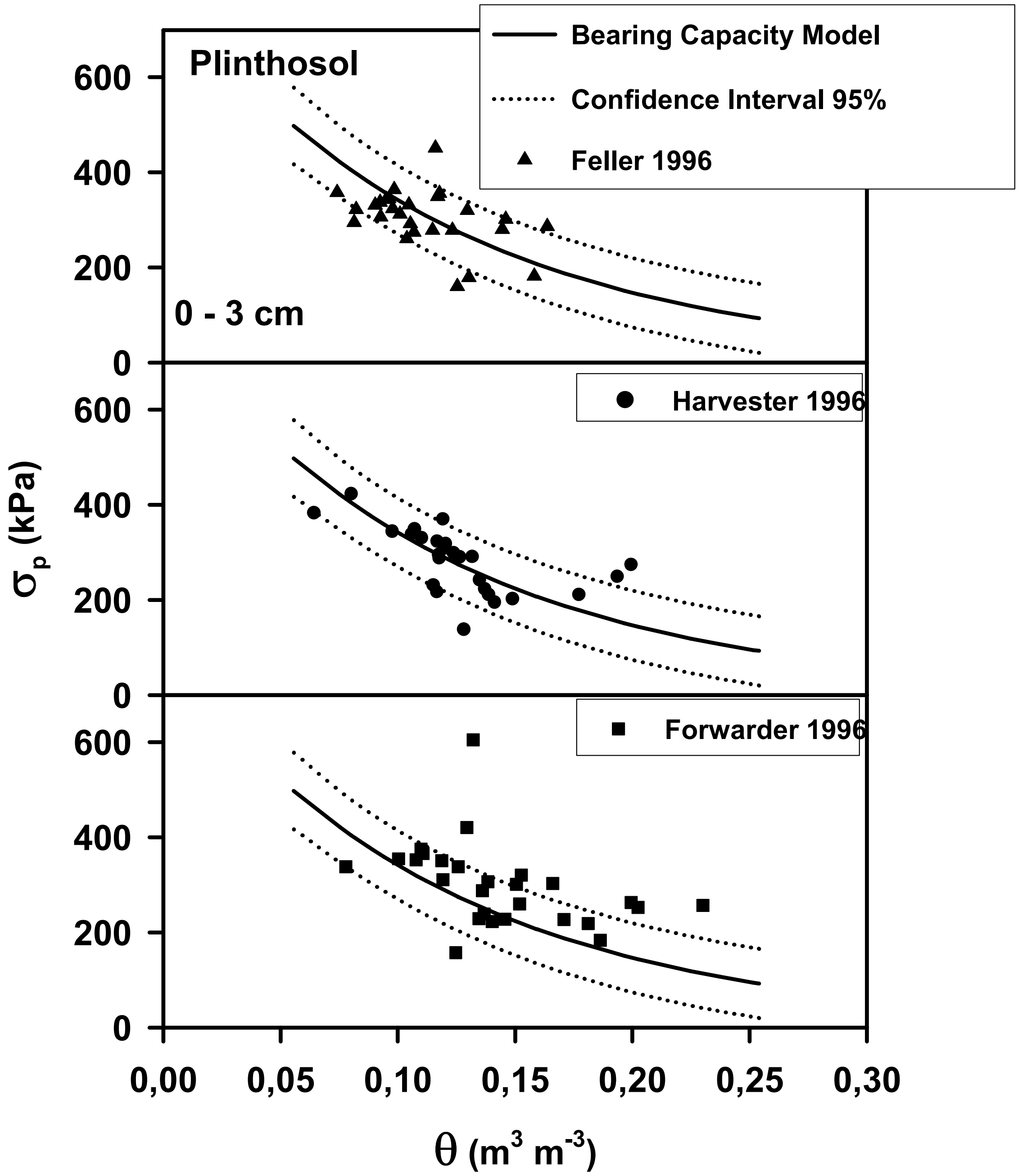

Figure 7. Bearing Capacity Model for a Plinthosol, after Feller-Büncher, Harvester and Forwarder operations, at 0-3 cm depth. Source: Dias Junior et al., (1999).

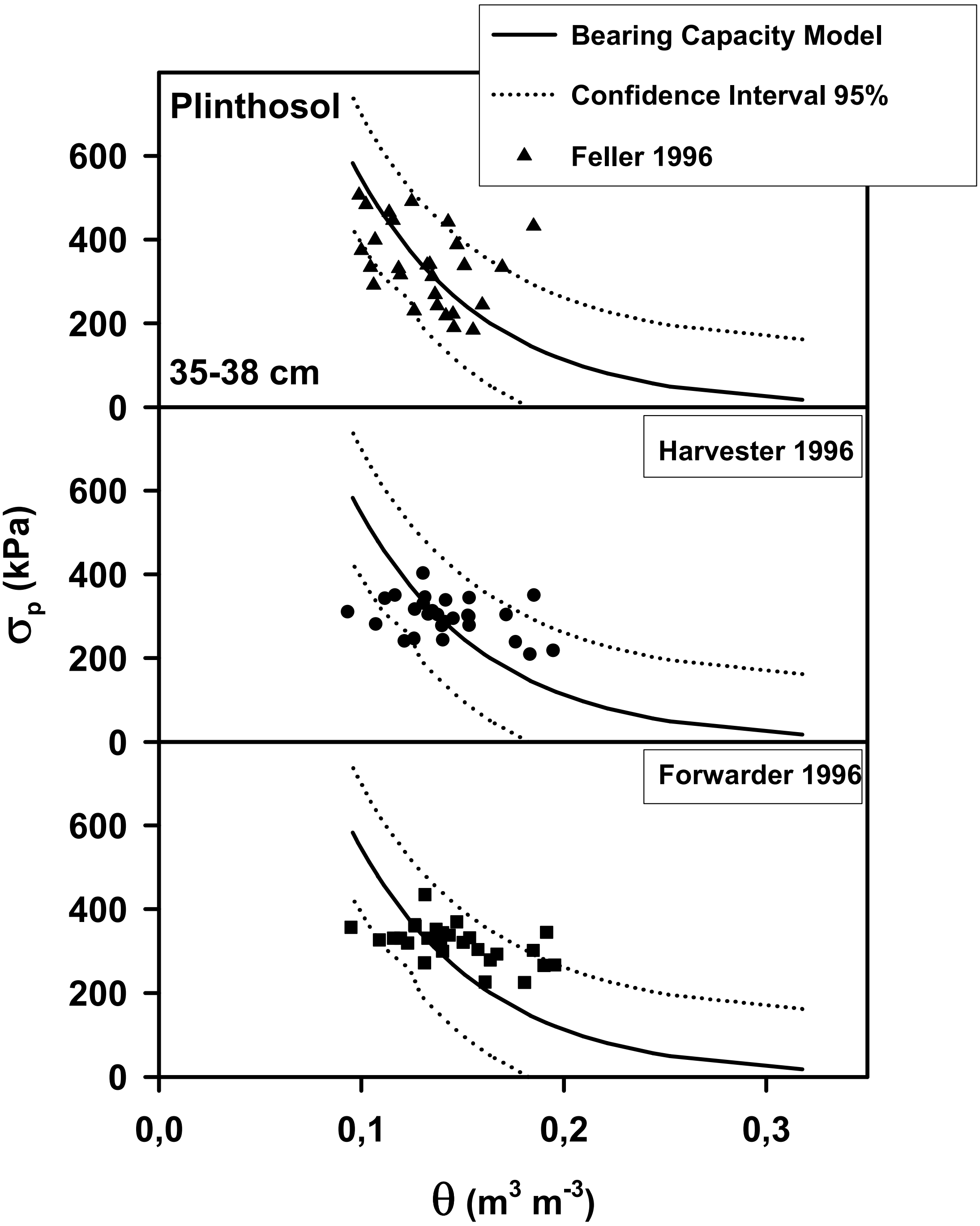

Figure 8. Bearing Capacity Model for a Plinthosol after Feller-Büncher, Harvester and Forwarder operations, at 35-38 cm depth. Source: Dias Junior et al., (1999).

To evaluate the harvest machinery effects on the soil structure, the Bearing Capacity Model, was divided into three regions: a) a 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) a region where 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) and smaller than the minimum precompression stress estimated with the equation of the confidence interval at 95% (σ_p minimum 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 minimum precompression stress estimated with the equation of the confidence interval at 95% (σ_p minimum estimated) (Figure 9).

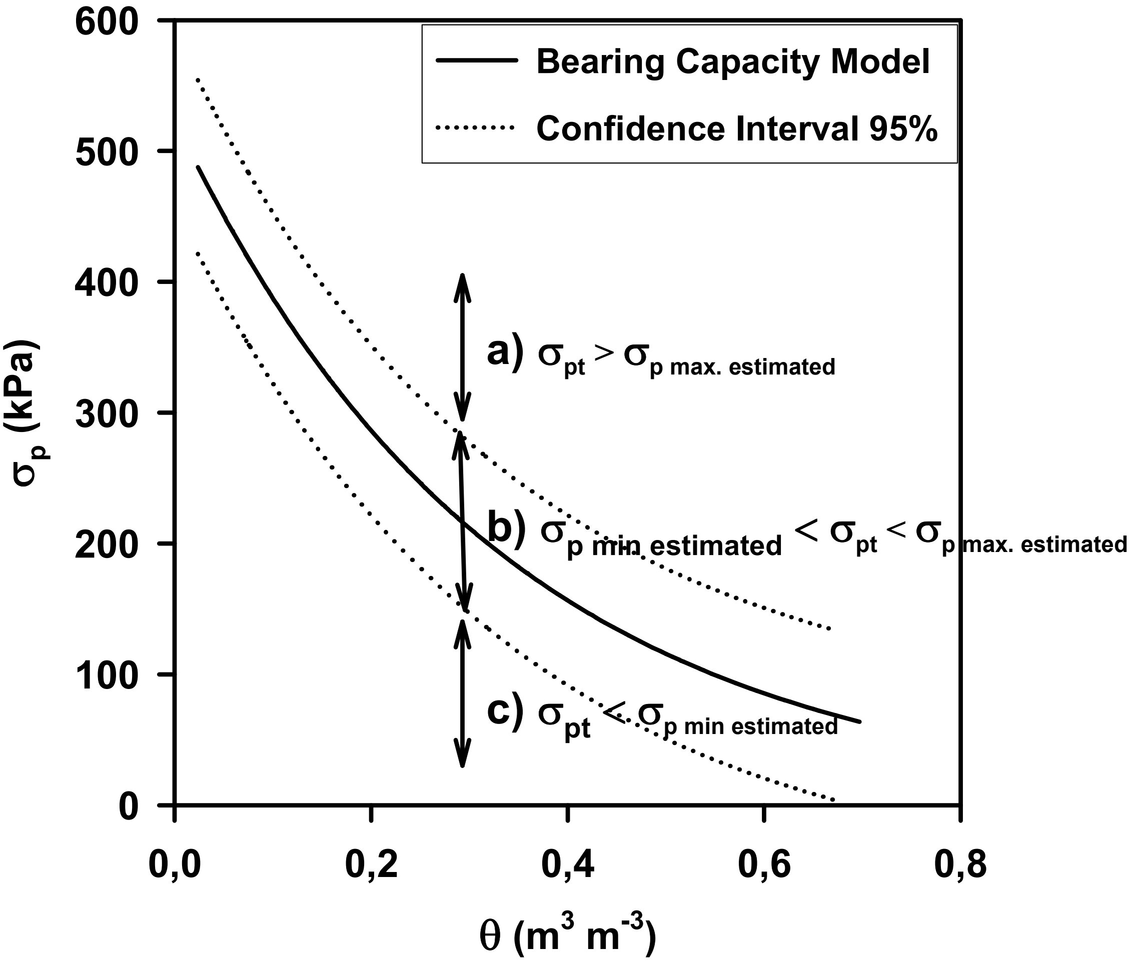

Figure 9. Bearing Capacity Model with the criteria used to estimate soil structure degradation. Source: Dias Junior et al., (2005).

Considering the criteria suggested in figure 9, and the results presented in figures 5 to 8, it was observed that the Feller-Büncher did not caused any soil structure degradation in both depth and soil classes; the Harvester caused soil structure degradation only in the Yellow Argisol at 0-3 cm depth (Figure 5) and the Forwarder, however, caused soil structure degradation in both soil classes at 0-3 cm depth (Figures 5 and 7) and at 35-38 cm depth the Forwarder did not caused any soil structure degradation (Figures 6 and 8). These results indicated that the operations performed with Forwarder were the one that caused more soil compaction.

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 9, was considered and the precompression stress as a function of volumetric watercontent were deter mined in 1996, 1998, 2000, 2002 and 2004 in the traffic line of the Forwarder, and plotted in figures 10, 11, 12 and 13 for the Yellow Argisol at 0-3 cm and 35-38 cm depth. Figure 10 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 (63%, 22%, 11%, 4% and 7%) and an increase in the percentage of soil samples in the region where there is no soil structure degradation (37%, 74%, 85%, 92% and 93%) indicating a natural recovered of the soil structure since no tillage operations was done during those years.

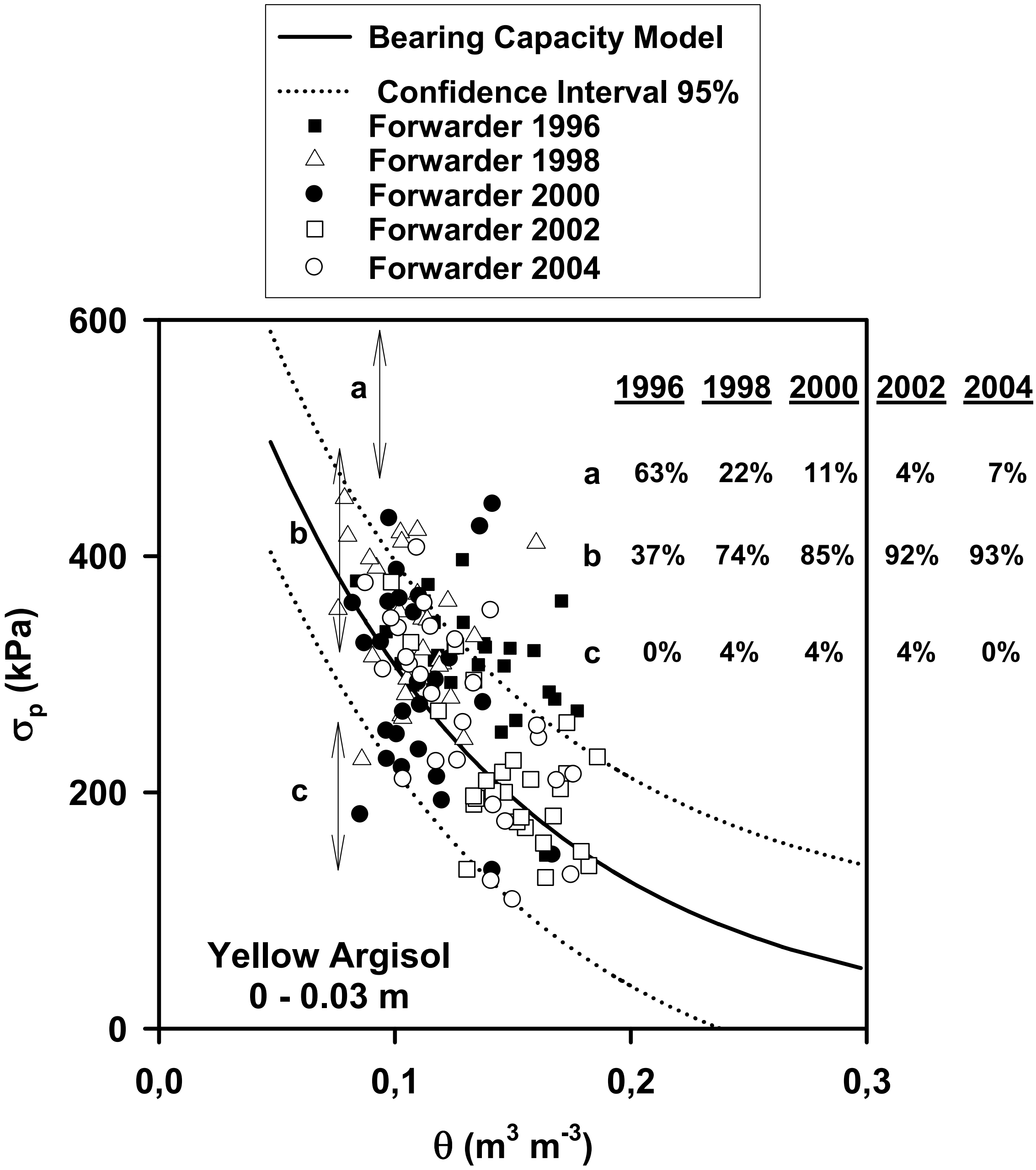

Figure 10. Bearing Capacity Model for a Yellow Argisol at 0-0.03 m depth. The symbols represent the values of the precompression stress determined in soil samples collected in 1996, 1998, 2000, 2002 and 2004, in the area where the Forwarder operations was done in 1996. (Source: Dias Junior, 2005).

Figure 11 shows that at 0-3 cm depth, the percentage of soil samples in the region where soil structure degradation had already happened increased from 7% before harvest in 2004 to 67% after harvest in 2004 and this value is closed to 63% after harvest in 1996, indicating a sustainable exploration of this area with eucalyptus plantation.

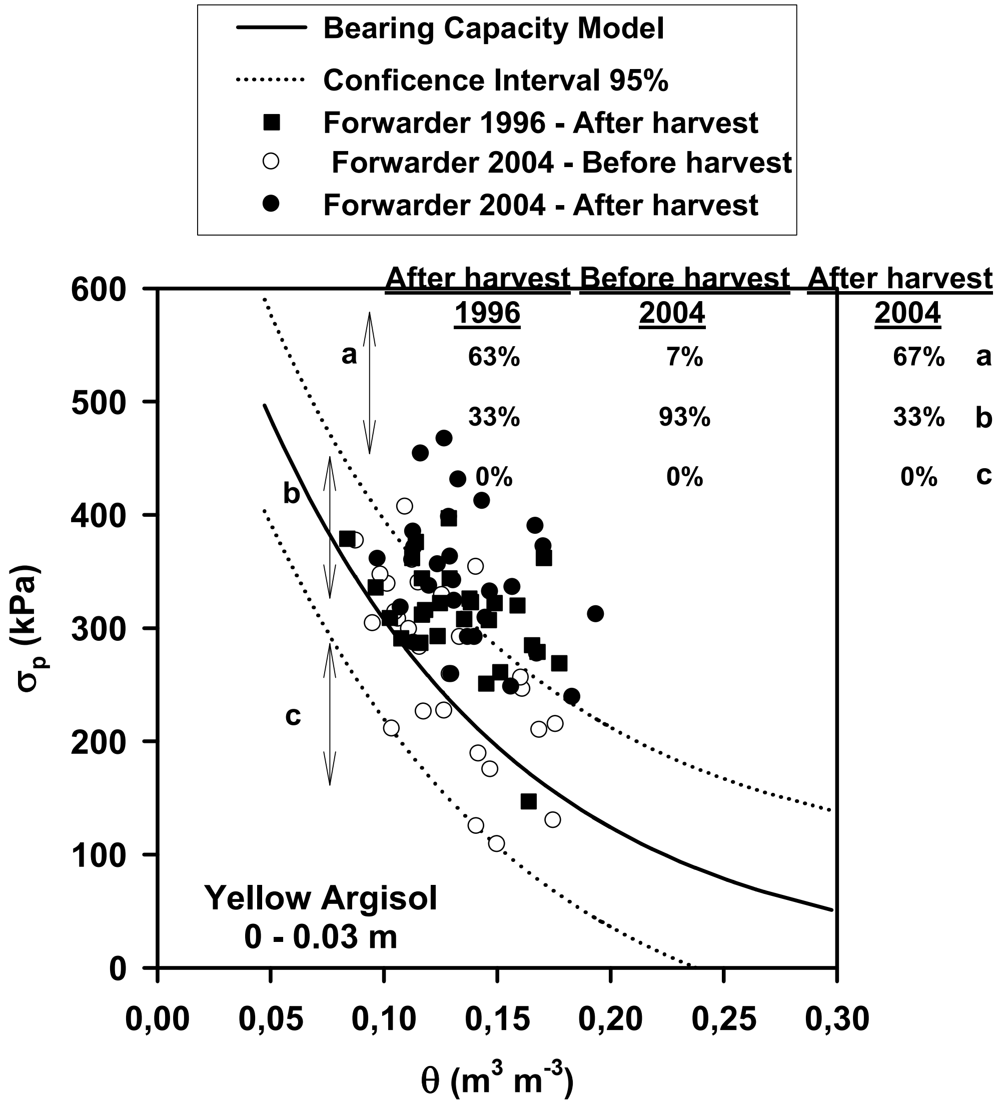

Figure 11. Bearing Capacity Model for a Yellow Argisol at 0-0.03 m depth. The symbols represent the values of the precompression stress determined in soil samples collected in 1996 after harvest, 2004 before harvest and 2004 after harvet, in the area where the Forwarder operations was done in 1996. (Source: Dias Junior, 2005).

In figure 12 and 13 it were observed the same behavior as it were observed in figures 10 and 11.

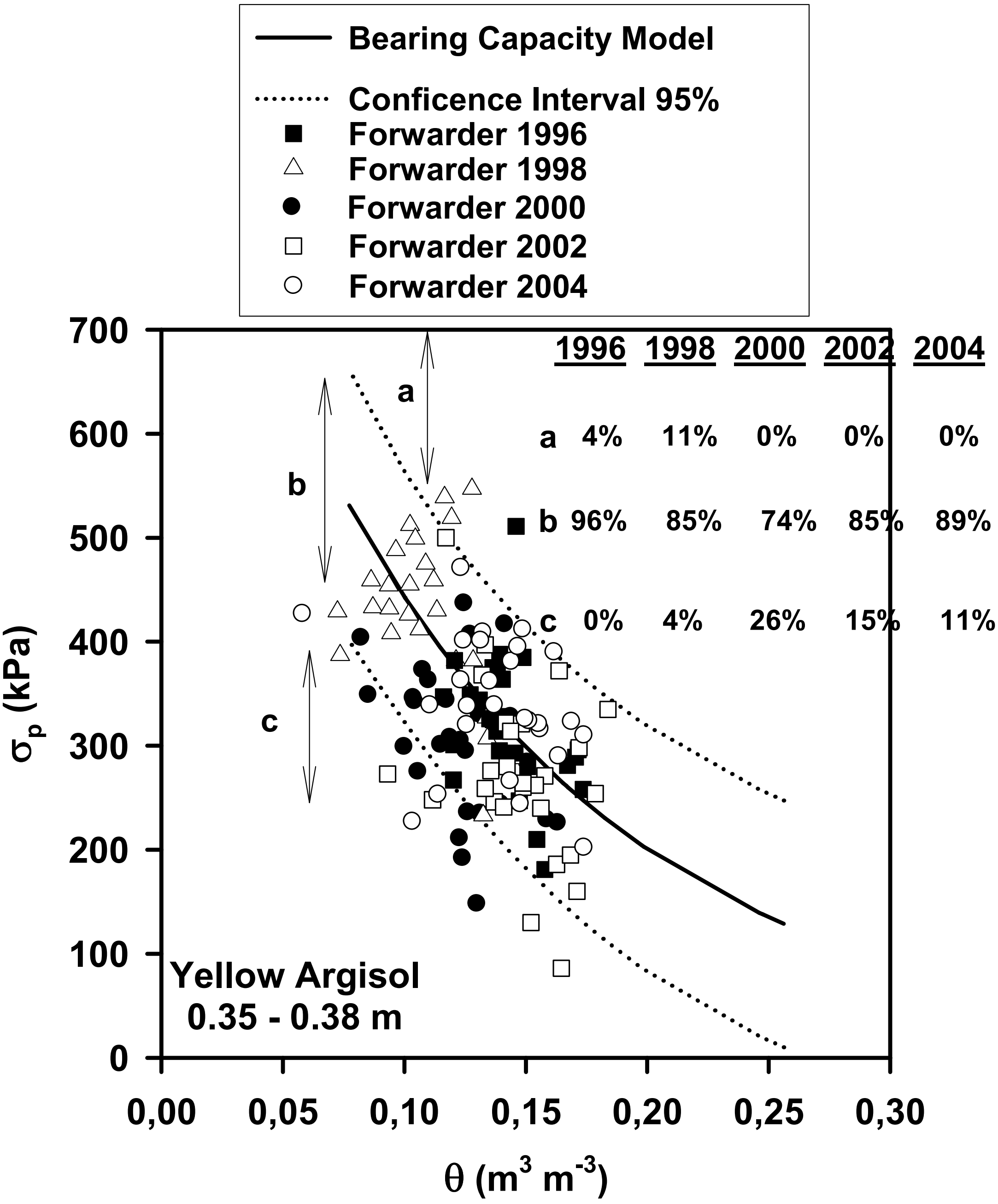

Figure 12. Bearing Capacity Model for a Yellow Argisol at 0.35-0.38 m depth. The symbols represent the values of the precompression stress determined in soil samples collected in 1996, 1998, 2000, 2002 and 2004, in the area where the Forwarder operations was done in 1996. (Source: Dias Junior, 2005).

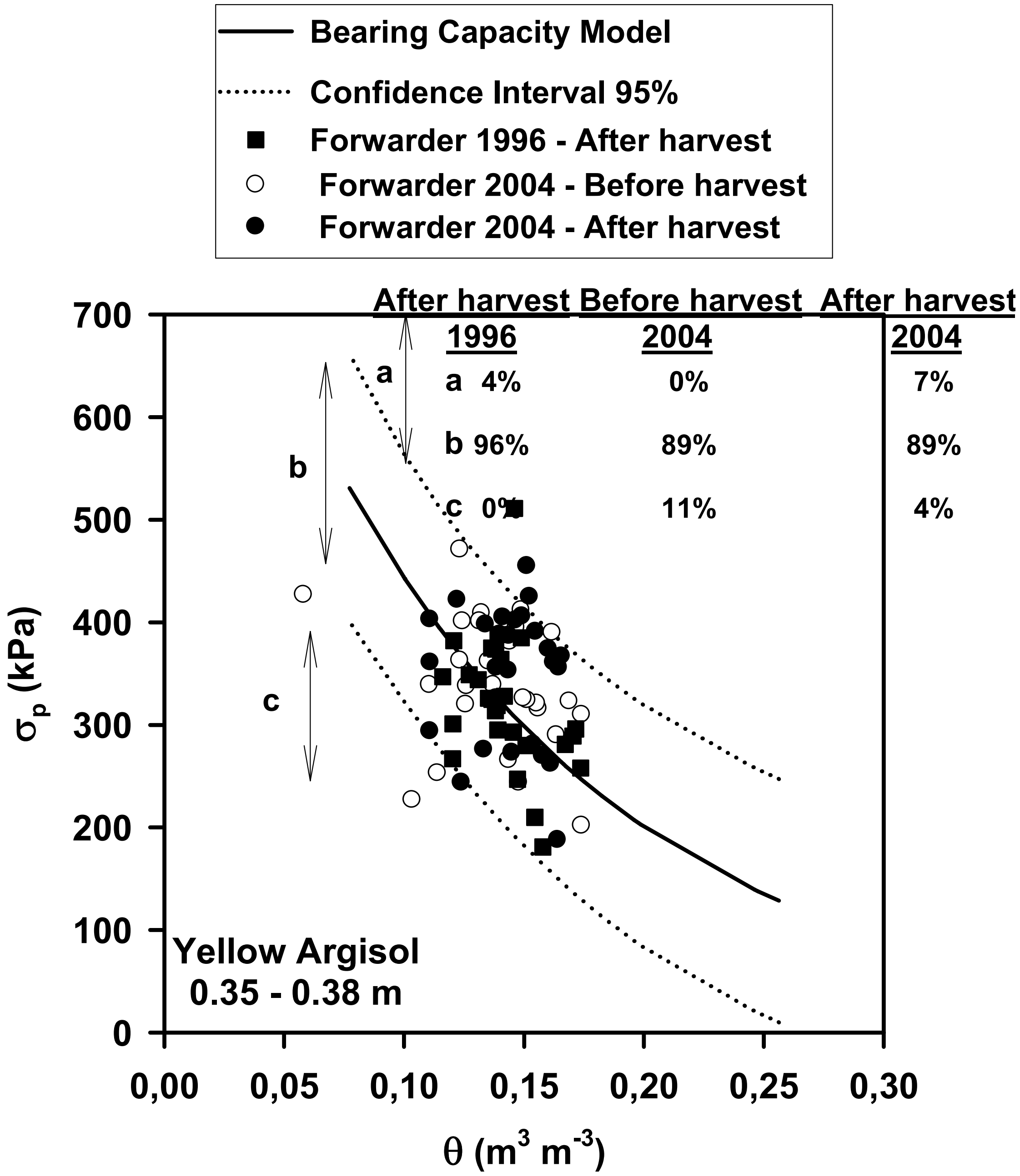

Figure 13. Bearing Capacity Model for a Yellow Argisol at 0.35-0.38 m depth. The symbols represent the values of the precompression stress determined in soil samples collected in 1996 after harvest, 2004 before harvest and 2004 after harvet, in the area where the Forwarder operations was done in 1996. (Source: Dias Junior, 2005).

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 eight 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.

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 1.

Table 1. 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 1, 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.

GENERAL CONSIDERATIONS

Several researchers have already demonstrated the causes and effects of soil compaction. These studies showed that the soil compaction is a limiting factor in agricultural production and a recovery of compacted areas, if possible, demands long time and high cost, therefore, a way that seems the most appropriate to avoid this problem, would be its prevention. Thus, the development of models that allow to foresee soil compaction would be very useful in the agriculture.

The researches done in the soil compressive behavior of some tropical soils indicate that the precompression stress may be used as an auxiliary criterion in planning the mechanized operations and to quantify the traffic effect on the soil structure.

REFERENCES

Anderson, T.C. and Lukas, R.G., 1981. Preconsolidation pressure predicted using Su/p' ratio. In: R.N. Yong and F.C. Townsend (editors). Laboratory shear strength of soil. Symposium ASTM. Special Technical Publication 740. Chicago, IL, 25 June 1980, Philadelphia, PA, pp.502-515.

Arvidsson, J., 2001. Subsoil compaction caused by heavy sugarbeet harvesters in southern Sweden I. Soil physical properties and crop yield in six field experiments. Soil Till. Res. 60, 67-78.

Barnes, K.K; Carleton, W.M.; Taylor, H.M.; Throckmorton, R.I. and Vanden Berg, G.E., 1971. Compaction of agricultural soils. Am. Soc. Agric. Eng. Monogr., St. Joseph, 471p.

Bicki, T.J., and Siemens, J.C., 1991. Crop response to wheel traffic soil compaction. Trans. Am. Soc. Agric. Eng., 34, 909-913.

Bingner, R.L.; and Wells, L.G., 1992. Compact - a reclamation soil compaction model part I. model development. Trans. Am. Soc. Agric. Eng., 35: 405-413.

Brumund, W.F.; Jonas, E. and Ladd, C.C., 1976. Estimating in situ maximum past (preconsolidation) pressure of saturated clays from results of laboratory consolidometer test. In: Transportation Research Board, National Research Council. Estimation of Consolidation Settlement. Special Report 163. National Academy of Science. Washington, DC, pp. 4-12.

Burmister, D., 1951. The application of controlled test methods in consolidation testing. In: Fifty -Four Annual Meeting of the ASTM. Symposium on Consolidation Testing of Soils. Special Technical Publication 126. Atlantic City, NJ. 18 June 1951, Philadelphia, PA, pp. 83-98.

Canarache, A.; Horn, R. and Colibas, I., 2000. Compressibility of soils in a long term field experiment with intensive deep ripping in Romania. Soil Till. Res. 56, 185-196.

Canillas, E. C. and Salokhe, V. M., 2002. A decision support system for compaction assessment in agricultural soils. Soil Till. Res. 65, 221-230.

Casagrande, A., 1936. The determination of the pre-consolidation load and its practical significance. In: Int. Conf. on Soil Mech. and Found. Eng., Proc. of the ICSMFE. Cambridge, MA, 22-26 June 1936. Col. 3. Cambridge, MA, pp. 60-64.

Culley, J.L.B. and Larson, W.E., 1987. Susceptibility to compression of a clay loam Haplaquoll. Soil Sci. Soc. Am. J., 51, 562-567.

Çarman, K., . Compaction characteristics of towed wheels on clay loam in a soil bin. Soil Till. Res. 65, 37-43.

Crawford, C.B., 1964. Interpretation of the consolidation tests. In: PROCEEDINGS OF THE AMERICAN SOCIETY OF CIVIL ENGINEERING, 1964. PROCEEDINGS. Evanston. Ill. p. 93-108.

Dauda, A. and Samari, A., 2002. Cowpea yield response to soil compaction under trator on a sandy loam soil in the semi-arid region of northern Nigeria. Soil Till. Res. 68, 17-22.

Defossez, P. and Richard, G., 2002. Models of soil compaction due to traffic and their evaluation. Soil Till. Res. 67, 41-64.

Dias Junior, M. S., 1994. Compression of three soils under long-term tillage and wheel traffic. Ph.D Thesis, Michigan State University.

Dias Junior, M. S., 2000. Compactação do solo. In R.F. Novais; V.H. Alvarez V and C.E.G.R. Schaefer (Editors). Topics in Soil Science. Soc. Bras. Ci. Solo. pp. 55-94.

Dias Junior, M. S., 2002a. Compactação do solo. Relatório de Pesquisa. Aracruz Celulose S.A. 72pp.

Dias Junior, M. S., 2002b. Avaliação de impactos de sistemas de colheita nas características físicas dos solos. Relatório de Pesquisa. Celulose Nipo-Brasileira S.A.113 pp.

Dias Junior, M.S., Ferreira, M.M., Fonseca, S., Silva, A.R., Ferreira, D.F., 1999. Avaliação quantitativa da sustentabilidade estrutural dos solos em sistemas florestais na região de Aracruz – ES. R. Árv**.**, 23, 371-380.

Dias Junior, M. S.; Leite, f. p.; Lasmar Junior, E and Araujo Junior, C. F. 2005. Traffic effect on the soil presconsolidation pressure due to Eucaliptus harvest operations. Scientia Agricola, 3:248-255.

Dias Junior, M. S. and Miranda, E.E.V., 2000. Comportamento da curva de compactação de cinco solos da região de Lavras (MG). Ci. Agrot. 24, 337-346.

Dias Junior, M. S. and Pierce, F.J., 1995. A simple procedure for estimating preconsolidation pressure from soil compression curves. Soil Tech., 8, 139-151.

Dias Junior, M. S. and Pierce, F.J., 1996a. Influência da história de tensão e da umidade na modelagem da compactação do solo. In: V.H. ALVAREZ V; L.E.F. FONTES and M.P.F., FONTES (editors). O solo nos grandes domínios morfoclimáticos do Brasil e o desenvolvimento sustentado. Soc. Bras. Ci. Solo, Viçosa, MG. pp.445-452.

Dias Junior, M. S. and Pierce, F.J., 1996b. Revisão de literatura: O processo de compactação do solo e sua modelagem. R. Bras. Ci. Solo, 20, 175-182.

Dürr, C. and Aubertot, J. N., 2000. Emergence of seedling of sufar beet (*Beta vulgairs* L.) as affected by aggregate size, roughness and position of aggregates in the seedbed. Plant Soil, 219, 211-220.

Gupta, S.C.; Hadas, A. and Schafer, R.L., 1989. Modeling soil mechanical behavior during compaction. In W.E. Larson; G.R. Blake; R.R Allmaras; W.B. Voorhees and S.C. Gupta (editors). Mechanics and related process in structured agricultural soils. NATO Applied Sciences 172. Kluwer Academic Publishers, The Netherlands. pp.137-152.

Gupta, S.C.; Hadas, A.; Voorhees, W.B.; Wolf, D.; Larson, W.E. and Schneider, E.C., 1985. Development of quids for estimating the ease of compaction of world soils. Bet Dagan, Israel. Research Report, Binational Agric. Res. Development, University of Minnesota, 178 pp.

Gysi, M., 2001. Compaction of a Eutric Cambisol under heavy wheel traffic in Switzerland: Field data and a critical state soil mechanics model approach. Soil Till. Res. 61, 133-142.

Hill, R.L. and Meza-Montalvo, M., 1990. Long- term wheel traffic effects on soil physical properties under different tillage systems. Soil Sci. Soc. Am. J., 54, 865-870.

Hillel, D., 1982. Introduction to Soil Physics. San Diego, Academic Press, 1982. 364pp.

Holtz, R.D. and Kovacs, W.D., 1981. An introduction to Geotechnical Engineering. Prentice-Hall, Inc., Englewood Cliffs, NJ, 733pp.

Horn, R., 1998. Compressibility of arable land. Catena Sup., 11:53-71.

Horn, R. and Rostek, J., 2000. Subsoil compaction process – State of Knowlledge.. In Horn, R.; van den Akker, J. J. H. And Arvidsson (Editors). Subsoil compaction. Sistribution, processes and consequences. Advances in Geoecology, 32 Advances in Geoecology, 32, 44-54.

Horn, R.; van den Akker, J. J. H. And Arvidsson. J., 2000. Subsoil compaction. Sistribution, processes and consequences. Advances in Geoecology, 32, 462p.

Jamiolkowski, M., Ladd, C. C., Germaine, J. T. and Lancellota, R., 1985. New development in field and laboratory testing of soils. In: Publications Committee of XI ICSMFE (editor). Proc. of the Eleventh Int. Conf. on Soil

Mech. and Found. Eng. San Francisco, Ca 12-16 August 1985. Netherlands, pp. 57-153.

Ishaq, M; Ibrahim, M.; Hassan, A.; Saeed, M. and Lal, R., 2001. Subsoil compaction effects on crop in Punjab, Pakistan: II. Root growth and nutrient uptake of wheat and sorghum. Soil Till. Res. 60, 153-161.

Jose, B.T.; Sridharan, A. and Abraham, B.M., 1989. Log-log method for determination of preconsolidation pressure. Geotech. Testing J., 12, 230-237.

Kondo, M.K., 1998. Compressibilidade de Três latossolos sob diferentes usos. M.S. Thesis, Universidade Federal de Lavras.

Kondo, M.K. and Dias Junior, M.S., 1997. Compressibilidade de um Latossolo Vermelho amarelo sob diferentes usos. Anais do Congresso Brasileiro de Ciência do Solo, 26, Rio de Janeiro, RJ, pp. 26.

Kondo, M.K. and Dias Junior, M.S., 1999. Compressibilidade de três latossolos em função da umidade e uso. R. Bras. Ci. Solo, 23:211-218.

Larson, W.E.; Blake, G.R.; Allmaras, R.R.; Voorhees, W.B. and Gupta, S.C., 1989. Mechanics and related processes in structured agricultural soils. The Netherlands, Kluwer Academic Publishers. 273p. (NATO Applied Science, 172).

Larson, W.E. and Gupta, S.C., 1980. Estimating critical stress in unsaturated soils from changes in pore water pressure during confined compression. Soil Sci. Soc. Am. J. 44, 1127-1132.

Larson, W.E.; Gupta, S.C. and Useche, R. A., 1980. Compression of agricultural soils from eight soil orders. Soil Sci. Soc. Am. J. 44, 450-457.

Lebert, M.; Burger, N. and Horn, R., 1989. Effects of dynamic and static loading on compaction of structured soils. In: W.E. Larson; G.R. Blake; R.R Allmaras; W.B. Voorhees and S.C. Gupta (editors). Mechanics and related process in structured agricultural soils. NATO Applied Sciences 172. Kluwer Academic Publishers, The Netherlands. pp.73-80.

Lebert, M. and Horn, R., 1991. A method to predict the mechanical strength of agricultural soils. Soil Till. Res., 19, 275-286.

Leonards, G.A., 1962. Foundation Engineering. New York, McGraw-Hill Book Company, 1136p.

MacNabb, D.H. and Boersma, L., 1993. Evaluation of the relationship between compressibility and shear strength of Andisols. Soil Sci. Soc. Am. J., 57:923-929.

McBride, R.A.; Joosse, P.J., 1996. Overconsolidation in agricultural soils: II. Pedotranfer functions for estimating preconsolidation stress. Soil Sci. Soc. Am. J., 60: 373-380.

Muller, L.; Tille, P. and Kretschmer, H., 1990. Trafficability and workability of alluvial clay soils in response to drainage status. Soil Till. Res. 16, 273- 287.

O'Sullivan, M.F., 1992. Uniaxial compaction effects on soil physical properties in relation to soil type and cultivation. Soil Til. Res., 24:275-286.

Pedrotti, A. and Dias Junior, M.S., 1996. Compactação do solo: como evitá-la. Agrop. Catarinense, 9, 50-52.

Pytka, J., 2001. Load effect upon soil stress and deformation state in structured and disturbed sandy loam for two tillage treatment. Soil Till. Res. 59, 13- 25.

Radford, B. J.; Yule, D. F.; McGarry, D. and Playford, C., 2001. Crop response to applied soil compaction and to compaction repair treatment. Soil Till. Res. 61, 155-170.

Sällfors, G., 1975. Preconsolidation pressure of soft high plastic clays. Thesis. Department of Geotechnical Engineering, Gothenburg.

Schmertmann, J.H., 1955. The undisturbed consolidation behavior of clay. Trans. ASCE, 120, 1201-1233.

Servadio, P.; Marsili, A.; Pagliai, M.; Pellegrini., S. and Vignozzi., 2001. Effect on some clay soil qualities following the passage of rubber-tracked and wheeled tractors in central Italy. Soil Till. Res. 61, 143-155.

Silva, A.R.; Lima, J.M. and Dias Junior, M.S., 1999. Efeito da adsorção de fosfato em parâmetros físicos e na compressibilidade de solos tropicais. R. Bras. Ci.Solo, 23:219 -226.

Smucker, A.J.M. and Erickson, A.E., 1989. Tillage and compactive modifications of gaseous flow and soil aeration. In: W.E. Larson; G.R. Blake; R.R Allmaras; W.B. Voorhees and S.C. Gupta (editors). Mechanics and related process in structured agricultural soils. NATO Applied Sciences 172. Kluwer Academic Publishers, The Netherlands. pp. 205-221.

Soane, B.D. and van Ouwerkerk, C., 1994. Soil compaction in crop production. Amsterdam, Elsevier, 660pp.

Stone, J.A., 1987. Compaction and the surface structure of a poorly drained soil. Transaction of the American Society of Agricultural Engineering. St. Joseph, 30, 1370-1373.

Tardieu, F. 1988. Analysis of the spatial variability of maize root density: I. Effect of wheels compaction on the spatial arrangement of roots. Plant Soil, 107,259-266.

Taylor, H.M., 1971. Effects of soil strength on seedling emergence, root growth and crop yield. In: Barnes, K.K.; Carleton, W.M.; Taylor, H.M.; Throckmorton, R.I. & Vanden berg, G.E. eds. Compaction of agricultural soils. St. Joseph. pp. 292-305.(ASAE. Monogr.)

Veenhof, D.W. and McBride, R.A., 1996. Overconsolidation in agricultural soils: I. compaction and consolidation behavior of remolded and structured soils. Soil Sci. soc. Am. J., 60:362-373.