SEÇÃO I - FÍSICA DOLO SOLO

SOIL COMPACTION AND EUCALYPTUS GROWTH IN RESPONSE TO FORWARDER TRAFFIC INTENSITY AND LOAD[1]

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SUMMARY

During timber exploitation in forest stands harvesting machines pass repeatedly along the same track and can cause soil compaction, which leads to soil erosion and restricted tree root growth. The level of soil compaction depends on the number of passes and weight of the wood load. This paper aimed to evaluate soil compaction and eucalyptus growth as affected by the number of passes and wood load of a forwarder. The study was carried out in Santa Maria de Itabira county, Minas Gerais State – Brazil, on a seven-year-old eucalyptus stand planted on an Oxisol. The trees were felled by chainsaw and manually removed. Plots of 144 m^2 (four rows 12 m long in a 3 x 2 m spacing) were then marked off for the conduction of two trials. The first tested the traffic intensity of a forwarder which weighed 11,900 kg and carried 12 m^3 wood (density of 480 kg m^{-3}) and passed 2, 4, and 8 times along the same track. In the second trial, the forwarder carried loads of 4, 8, and 12 m^3 of wood, and the machine was driven four times along the same track. In each plot, the passes affected four rows. Eucalyptus was planted in 30 x 30 x 30 cm holes on the compacted tracks. The soil in the area is clayey (470 clay and 440 g kg^{-1} sand content) and at depths of 0–5 cm and 5–10 cm, respectively, soil organic carbon was 406 and 272 g kg^{-1} and the moisture content during the trial 248 and 249 g kg^{-1}. These layers were assessed for soil bulk density and water-stable aggregates. The infiltration rate was measured by a cylinder infiltrometer. After 441 days the measurements were repeated, with additional analyses of: soil organic carbon, total nitrogen, N-NH_4^+, N-NO_3^-, porosity, and penetration resistance. Tree height, stem diameter, and stem dry matter were measured. Forwarder traffic increased soil compaction, resistance to penetration and microporosity while it reduced the geometric mean diameter, total porosity, macroporosity and

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infiltration rate. Stem dry matter yield and tree height were not affected by soil compaction. Two passes of the forwarder were enough to cause the disturbances at the highest levels. The compaction effects were still persistent 441 days after forwarder traffic.

Index terms: soil bulk density, water-stable aggregates, soil penetration resistance, porosity, soil organic carbon, infiltration.

RESUMO: *COMPACTAÇÃO DO SOLO E CRESCIMENTO DE EUCALIPTO INFLUENCIADOS PELA INTENSIDADE DE TRÁFEGO E CARGA DE UM FORWARDER*

Em povoamentos florestais, durante a retirada de madeira, as máquinas trafegam numa mesma linha várias vezes, o que pode causar a compactação do solo e, como conseqüência, facilitar o processo erosivo e dificultar o crescimento de raízes. O grau de compactação, além do número de passadas da máquina, pode também ser afetado pelo peso de madeira transportado. Este trabalho teve como objetivo avaliar a compactação do solo e o crescimento de eucalipto de acordo com a intensidade de trânsito e a carga de madeira de um forwarder. O estudo foi realizado no município de Santa Maria de Itabira, MG, em um Latossolo Vermelho-Amarelo (LVA) oxídico-gibbsítico. Um povoamento de eucalipto com sete anos de idade foi abatido por motosserra, sendo a madeira retirada da área manualmente. Em seguida, demarcaram-se parcelas de quatro entrelinhas de árvores com 12 m de comprimento (espaçamento 3 x 2 m), com área de 144 m^2 cada. Dois ensaios foram feitos. No primeiro, testou-se o efeito da intensidade de trânsito, no qual um forwarder, com tara de 11.900 kg, foi carregado com 12 m^3 de madeira (densidade de 480 kg m^{-3}) e dirigido sobre a mesma entrelinha por 0, 2, 4 e 8 vezes. No segundo, o forwarder recebeu cargas correspondentes a 4, 8 e 12 m^3 de madeira e dirigido quatro vezes sobre a mesma entrelinha. Em cada parcela, quatro entrelinhas foram compactadas pelas rodas. Foi realizado o plantio de eucalipto em covas de 30 x 30 x 30 cm, abertas sobre as trilhas compactadas. O teor de carbono orgânico total (COT) era de 406 e 272 g kg^{-1} e a umidade atual do solo era de 248 e 249 g kg^{-1} nas camadas de 0–5 e 5–10 cm de profundidade, respectivamente. O teor de argila era de 470 e de areia 440 g kg^{-1}. As avaliações realizadas após a aplicação dos tratamentos, nas camadas de 0–5 e 5–10 cm de profundidade, foram: densidade do solo e agregados estáveis em água. Determinou-se, ainda, a velocidade de infiltração básica (VIB) pelo método do infiltrômetro de cilindro. Após 441 dias, estas mensurações foram realizadas novamente, sendo acrescidas de outras análises: COT, N total, N-NH_4^+, N-NO_3^-, porosidade e resistência à penetração. Nas plantas, foram mensurados altura, diâmetro à altura do peito e matéria seca de tronco. Verificou-se que o trânsito do forwarder aumentou a densidade, microporosidade e a resistência do solo à penetração e reduziu o diâmetro médio geométrico, a porosidade total, a macroporosidade e a infiltração de água no solo. Não houve efeito da compactação sobre a produção de matéria seca de tronco e altura das plantas. A maior parte dos efeitos da compactação foi manifestada por apenas duas passadas do forwarder. Os efeitos da compactação ainda permaneciam no solo após 441 dias do trânsito do forwarder.

Termos de indexação: densidade do solo, agregados estáveis em água, resistência do solo à penetração, porosidade, carbono orgânico, infiltração.

INTRODUCTION

The constant and significant weight increase of agricultural and forest vehicles over the last decades in Brazil has caused concern in view of the possible long-term consequences on eucalyptus yield in soils under traffic. The imminent loss in forest productivity is great since traffic is a repeated action in stands (Balbuena et al., 2000). Machine traffic is admittedly one of the main origins of soil compaction, which has a negative knock-on effect on tree growth (Wert & Thomas, 1981; Froehlich et al., 1985; Startsev & McNabb, 2000).

Repeated traffic in a same area intensifies the damage done to the soil structure with consequent reductions in crop yields in the first as well as in the following years of production (Håkansson & Reeder, 1994; Lal, 1996; Jorajuria et al., 1997). During the removal of the wood from forest stands the machines drive along one and the same row several times. This can cause soil compaction and, consequently, hinder root growth. It was observed that in harvest systems with a forwarder that poses a high compaction risk, the control of the number of machine passes could reduce the impact caused by soil compaction (Nugent et al., 2003). Furthermore, the degree of compaction is related to the weight of the wood load, leading to soil deformation when the pressure on the soil exceeds the load support capacity (Dias Júnior, 2000; Dias Júnior et al., 2005; Silva et al., 2007a,b).

Compaction affects the physical, chemical and biological soil properties. It is worldwide an important cause for soil degradation of agricultural soils (Håkansson et al., 1988; Håkansson & Voorhees, 1998). It can interfere in the C and N cycle by altering soil aeration or the microbial community, which can slow down the decomposition of the organic matter and increase N gas losses (Breland & Hansen, 1996; Jensen et al., 1996).

Compaction increases soil bulk density and penetration resistance and reduces macroporosity, aeration, infiltration and water storage in the soil (Alakukku & Elonen, 1994; Panayiotopoulos et al., 1994; Ishaq et al., 2001a; Silva, 2005). A reduction of water infiltration into the soil, caused by the compaction of the surface layer, can result in increased surface runoff and erosion (Kayombo & Lal, 1994). An increase in soil penetration resistance beyond values that vary from 1.5 to 3.0 MPa can restrict root growth, according to Grant & Lafond (1993), and from 2.0 to 4.0 MPa, according to Oussible et al. (1992) and Arshad et al. (1996). Jakobsen & Greacen (1985) studied the compaction caused by forwarders in pine tree areas. They observed that the values of soil penetration resistance increased by 0.2 to 0.3 MPa at each machine pass.

The persistence of soil compaction caused by machinery traffic has been reported by several scientists (Black et al., 1976; Pollard & Elliott, 1978; Voorhees et al., 1978; Logsdon et al., 1992; Lal, 1996). Some of these studies showed that the effects of the compaction are only temporarily harmful; still, in most cases, little or no modification of compaction was observed.

This study aimed to evaluate soil compaction and eucalyptus growth as related to the traffic intensity and wood load of a forwarder.

MATERIAL AND METHODS

The study was conducted in the county of Santa Maria de Itabira, MG (19 ° 23 ' 58 " S and 42 ° 54 ' 12 " W; 1.273 m asl). The soil in the area is a Red Yellow Latosol (Oxisol), clayey (470 clay and 440 g kg^{-1} sand content) at depths of 0–5 cm and 5–10 cm; respectively, soil organic carbon (Walkley & Black, 1934) was 406 and 272 g kg^{-1}, the soil bulk density 0.94 and 0.97 kg dm^{-3} and the moisture content during the trial 248 and 249 g kg^{-1}. A seven-year-old eucalyptus stand with downhill oriented rows (3 by 2 m spacing) was cut down by chainsaw. Then, four blocks of 1,152 m^2 (96 m length by 12 m width) each, encompassing 192 trees, were marked off. Two trials were conducted. In the first, the effect of the traffic intensity was tested, in which a forest tractor with hydraulic loader arm (Valmet forwarder, model 636 S, 112 hp, weighing 11,900 kg, and front tires with 29 pounds and the rear tires with 53 pounds, was loaded with 12 m^3 wood (density of 480 kg m^{-3}) and driven along the same track 0, 2, 4, and 8 times. The compacted area in each row was 1.0 m wide, i.e., 0.5 m for each tire. In the second trial, the forwarder was loaded with 4, 8, and 12 m^3 of wood and driven four times along the same track. In each treatment four rows were compacted, i.e., eight tracts, of which the inner four were used for the assessments. The total area of each plot was 144 m^2 (four rows 12 m long and spaced of 3 m from each other). A central plot of 19.2 m^2 (four 8 m long rows and 0.6 m wide tracks) was used in the evaluations.

The actual soil moisture was 248 and 249 g kg^{-1} in the layers of 0–5 and 5–10 cm, respectively, and corresponded to 124 and 124.5 % of the equivalent moisture. Five weeks after the treatment application seedlings of *Eucalyptus grandis* were planted in holes (30 x 30 x 30 cm) along the tracks compacted by the forwarder wheels.

The following soil properties were evaluated in the beginning (T_0) and after the application of the treatments: soil bulk density by the volumetric ring method (Embrapa, 1997); infiltration rate (IR) by the cylinder infiltrometer method (Cerdà, 1996); and water-stable aggregates (Embrapa, 1997), for which the soil samples were moistened 2 h before mechanic agitation in water. The geometric mean diameter was obtained according to Kemper & Rosenau (1986), after the evaluation of water-stable aggregates. These evaluations were performed randomly in five replications, in soil samples collected from the forwarder tracks, at the depths 0–5 and 5–10 cm (with exception of IR).

After 441 days (T_{441}) these measurements were repeated (six replications) in soil samples taken from the middle between two planting spots along the compacted tracks, and additional analyses performed for: total organic carbon (COT), total N, N-NH_4^+, and N-NO_3^-. COT was obtained by soil sample wet oxidation with potassium dichromate in sulfuric medium (Walkley & Black, 1934); total N was obtained by the Kjeldahl method (Bremner & Mulvaney, 1982); and mineral N (N-NH_4^+ and N-NO_3^-) was extracted during 10 min with KCl 1 mol L^{-1} solution (10 g soil:50 mL). Colorimetric methods were used to determine N-NO_3^- (Yang et al., 1998) and N-NH_4^+ (Kempers & Zweers, 1986). Undisturbed soil samples were collected at depths of 0–5 and 5–10 cm, using rings of PVC tubes (97.6 cm^3). Microporosity was measured in these samples by the method of the porous plate apparatus, and the total porosity and macroporosity were calculated (Embrapa, 1997). After soil moisture equilibrium at a tension of 0.006 MPa in the porous plate apparatus, soil penetration resistance was measured by an electronic penetrometer with a constant penetration speed of 4 cm min^{-1} and a cone with a base diameter of 4 mm and angle of 30°. The penetrometer was equipped with a linear actuator and load cell of 20 kg linked to a microcomputer for data acquisition. In the geometric centre of each sample, at a depth of 5 to 45 mm, a resistance reading was obtained at every 0.5 mm, completing a total of 80 readings, which were used to calculate the mean soil penetration resistance of each sample.

Tree height, diameter at breast height (DBH) and stem dry matter were measured 406 days after planting. All trees of each treatment were measured and the three most representative chosen to be felled and evaluated.

The monthly precipitation values during the conduction of the experiment are shown in Figure 1.

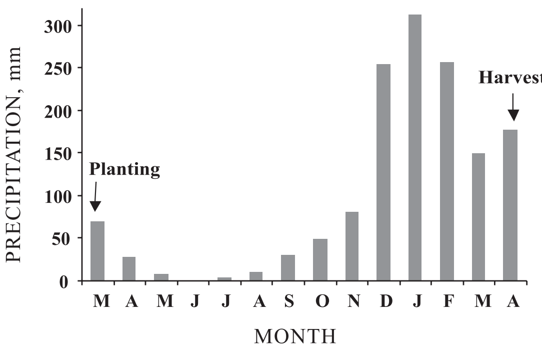

Figure 1. Monthly precipitation in eucalyptus stand during the experiment.

In the experiment of number of passes the data were subjected to Analysis of Variance (ANOVA), of correlation and of regression. The coefficients of the adjusted equations were assessed by F-test considering the mean square error of ANOVA of the experiment. Among the significant models, the one that presented a higher determination coefficient (R^2) was chosen. In the load experiment the data were subjected to Analysis of Variance and correlation and the means were compared in the clustering test of Scott-Knott ($p < 0.05$).

RESULTS AND DISCUSSION

There was an increase in the soil bulk density (D_S) caused by forwarder traffic (Figures 2a,b). The increment of the D_S reached 29 and 32 % immediately after eight forwarder passes, respectively, in the layers of 0–5 and 5–10 cm. In the second evaluation however, after 441 days, there was a recovery in the soil structure and the increment reached 15 and 24 % in the 0–5 and 5–10 cm layers, respectively. It was verified that 51 % (0–5 cm) and 73 % (5–10 cm) of the increment of the D_S, measured after soil compaction, persisted for 441 days, demonstrating that the surface layer has a greater resilience or capacity of recovering the initial stage after compaction, which can be explained by the higher number of wetting and drying cycles and the higher content of organic matter in the 0–5 cm layer compared to that at a depth of 5–10 cm.

Results of a study by Ishaq et al. (2001a) showed that the compaction effects on soil bulk density and penetration resistance continued for over 2 years. Similar results were obtained by Voorhees et al. (1986) and Hammel (1994), who observed increases in soil bulk density and, or, in penetration resistance which remained for four and three years, respectively, after compaction.

In a field trial, Koger et al. (1985) stated that most part of the total soil compaction induced by the traffic of a skidder occurred with the first passes of the engine. Seixas & Souza (1998) observed that around 80 % of the total compaction caused by 20 passes of a tractor with a lumber trailer occurred after the first five passes of the equipment, without any increase due to subsequent traffic. However, Jorajuria & Draghi (2000) reported that 90 % of the maximum increment in the soil bulk density of the surface layer (0–30 cm) occurred already with the first pass of a light tractor. According to Taylor et al. (1982), the first pass is considered to induce greatest changes in the soil structure, which is true for recently tilled soils. In consolidated soil, however, the compaction degree can be similar, regardless of the number of passes.

In the load experiment there was no difference between 4, 8 or 12 m^3 regarding the increase intensity of D_S measured in the first evaluation (T_0), but the D_S values were higher in all cases than in the control without forwarder traffic (Figure 2c). Heavier loads did not necessarily increase compaction, since there is an increase of the soil/tire contact surface, resulting in the redistribution of the soil load (Greacen & Sands, 1980; Çarman, 2002). After 441 days however the treatment with 4 m^3 of wood was the only one with a significant D_S decrease (Figure 2d). This demonstrates that heavier loads cause greater residual effects, limiting the capacity of soil recovery of the original density.

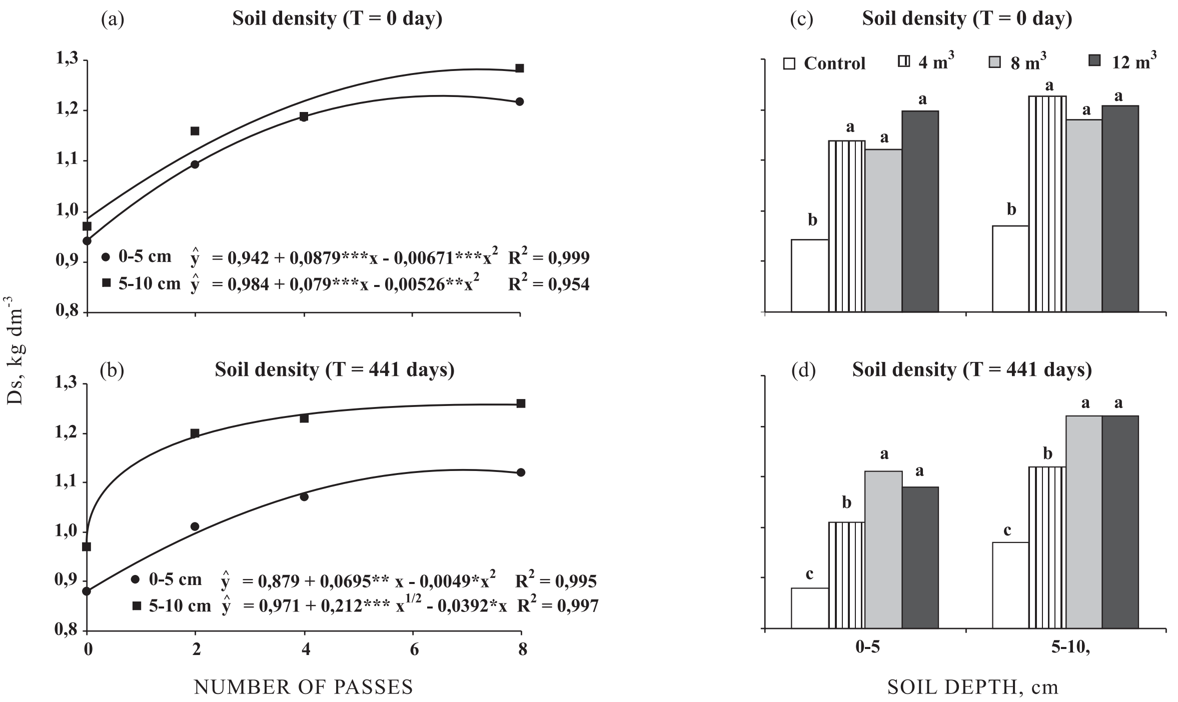

Figure 2. Soil bulk density as affected by the number of passes (a, b) and forwarder load (c, d) in eucalyptus stand after 0 and 441 days.

A lower total porosity and macroposity were observed in both layers 441 days after treatment application and a higher microposity in the 0–5 cm layer (Figure 3a,b). The increase of microporosity in this layer reached 53 % and the decrease of total porosity and macroporosity 16 and 68 %, respectively, with eight forwarder passes (Figure 3a). At this point the transformation of macropores into micropores through the effect of compaction becomes evident. In the 5–10 cm layer however the total porosity and macroporosity decreased by 19 and 51 %, respectively, after eight forwarder passes (Figure 3b).

However, in the load experiment there was no difference between the treatments with 4, 8 and 12 m^3, because 4 m^3 were enough to modify the soil porosity nearly as strongly as the higher loads (Figure 3c,d). Another hypothesis was mentioned by Silversides & Sundberg (1989), who evaluated soil compaction in forest areas and concluded that the soil-tire interface increases under higher axle loads, yet they assured that the pressure on the soil does not change since the increase in the contact area is proportional to the load increase.

Marsili et al. (1998) verified a decrease of macroporosity in the surface layer (0–10 cm) after two tractors passed once, which was intensified by four machine passes. These authors observed that the compaction effects were restricted to the surface layer. In the 10-20 cm layer there was no significant difference between uncompacted areas and those subjected to one or four passes of the two tractors. Wagger & Denton (1989) observed that the total porosity in the soil area under traffic was 21 % lower than in the area without traffic.

The correlation of total porosity with the bulk density (r = 0.99) and macroporosity (r = 0.80) was significant ($p < 0.01$) and positive. Macroporosity was also highly correlated with bulk density (r = 0.80).

The penetration resistance (PR) in the soil increased in response to compaction caused by forwarder traffic (Figure 4a), as observed in other studies (Marsili & Servadio, 1996; Marsili et al., 1998). The PR increased 4.2 and 3.7 times after eight machine passes in comparison to the uncompacted control (0 passes), respectively, in the 0–5 and 5–10 cm layers (Figure 4a). Only two forwarder passes accounted for 34 and 54 % of this increment, respectively, in the two layers. There was no difference between the treatments with 4, 8 and 12 m^3 of wood (Figure 4b). Balbuena et al. (2000) stated that under higher traffic intensity with a higher number of passes, the soil compaction degree rises independently of the axle load.

The maximum PR values were 2.36 and 2.02 MPa, respectively, in the 0–5 and 5–10 cm layers, with eight machine passes (Figure 4a). Theses values were lower than the 2.87 MPa obtained by Fernandes & Souza (2003) in the tracks after the last forwarder pass. The reason for this difference in PR observed in the two studies could be the soil moisture during the mensuration with the penetrometer, or the soil type or peculiarities of the machines (forwarder).

Compaction, as evidenced by higher penetration resistance, reduces soil penetration by roots (Unger & Kaspar, 1994). It was mentioned that PR values that exceed the range of 1.5 to 4.0 MPa are limiting to root growth and plant development (Oussible et al., 1992; Grant & Lafond, 1993; Martino & Shaykewich, 1994; Arshad et al., 1996; Ishaq et al., 2001b).

The correlation of PR with the bulk density (r = 0.75) and microporosity (r = 0.52) was positive and significant ($p < 0.001$) and negative with the total porosity (r = -0.75) and macroporosity (r = -0.76). Pagliai et al. (1992) and Marsili et al. (1998), in experiments dealing with soil compaction owing to machinery traffic, also obtained negative correlation between PR and macroporosity in the 0–10 cm layer.

There was a 32 and 47-fold decrease in the steady state infiltration rate (FIR) with eight forwarder passes, respectively, in the first (T_0) and second evaluation (T_{441}) (Figure 5a). Only 2 passes accounted for nearly the entire reduction, while there was no difference between the treatments with 4, 8 and 12 m^3 of wood (Figure 5b). Interestingly there was practically no recovery of this hydraulic soil property 441 days after the forwarder had compacted the soil.

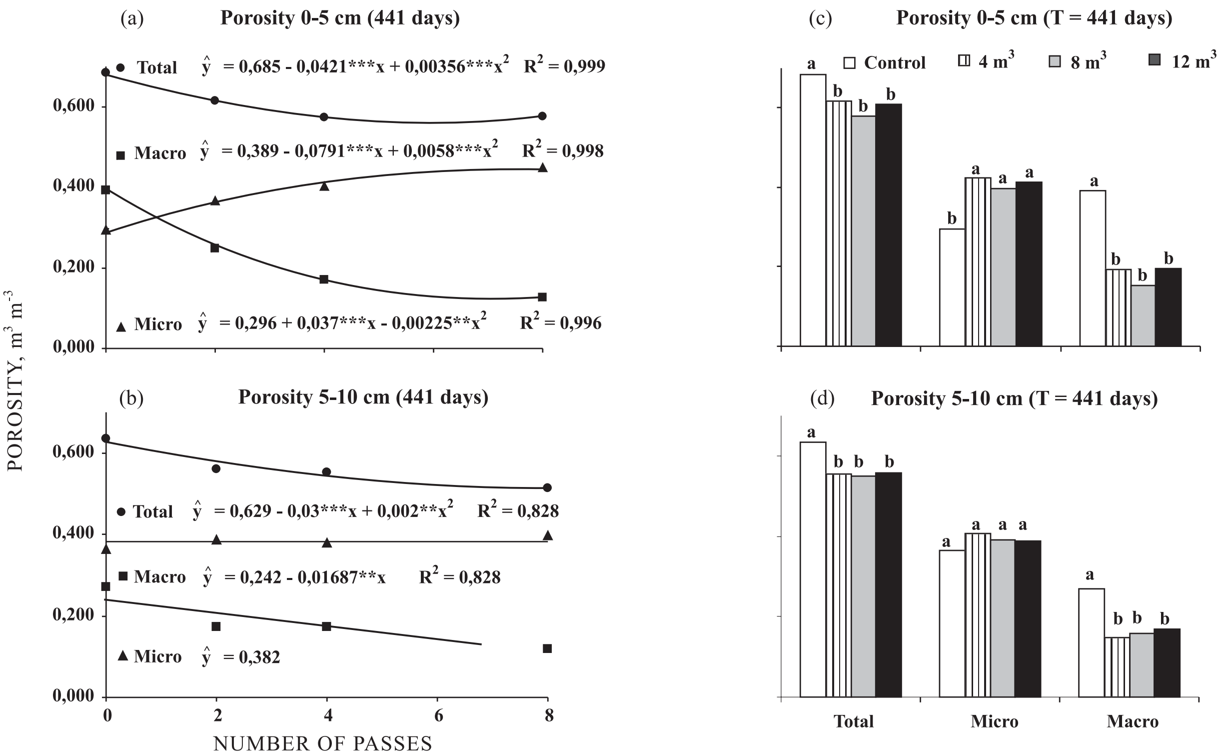

Figure 3. Soil porosity as affected by the number of passes (a, b) and forwarder load (c, d) in a eucalyptus stand, after 441 days.

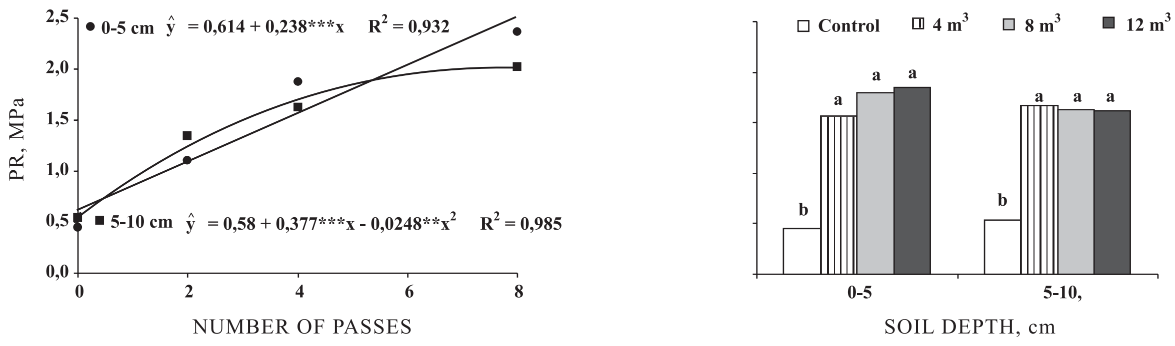

Figure 4. Soil penetration resistance as affected by the number of passes (a) and forwarder load (b) in eucalyptus stand after 441 days.

Startsev & McNabb (2000) also verified that the reduction in FIR, after the forwarder and skidder passes, had not been fully recovered three years after the occurrence of compaction. These authors observed that the greatest FIR reduction was caused by the first three machine passes while further traffic (7 and 12 passes) caused no significant alteration.

The correlation of FIR with the bulk density ($r = -0.68$), the PR ($r = -0.75$) and microporosity ($r = -0.52$) was a significant ($p < 0.001$) and negative, and positive with the total porosity ($r = 0.68$) and macroporosity ($r = 0.73$). Beutler et al. (2001) also found a significant ($p < 0.05$) and negative correlation of the FIR with PR ($r = -0.98$).

The reduction in FIR, caused by soil compaction, can be explained by modifications in the pore system, in other words, modified size distribution, elongation and vertical continuity of the pores. Marsili et al. (1998) ascribed the drop in hydraulic conductivity after four passes of two tractors to a reduction of the vertical continuity of the pores. These considerations can explain why the soil bulk density recovered a fraction of the initial stage after compaction, whereas the FIR did not recover, since it depends on the vertical continuity of the pores. The authors stated a high correlation between long vertical pores and the hydraulic conductivity and macroporosity.

FIR is a very important soil property regarding soil water storage and erosion. Soils with lower FIR are more exposed to erosion, due to the greater quantity of water that remains on the soil surface and, consequently, increases surface runoff (Cerdà, 1996, Marsili et al., 1998). The volume of water that does not infiltrate is lost and becomes inaccessible for plants.

There was a decrease of the geometric mean diameter (GMD) with the number of forwarder passes (Figure 6a,b). In the load experiment there was no difference between the treatments with 4, 8 and 12 m^3 of wood, except for 12 m^3 in the 5–10 cm layer at T_0. In this case, the GMD increase can be ascribed to physical aggregation forced by the forwarder wheel compression, which did however not form stable aggregates, as the decrease of 12 % of the GMD (from 1.58 mm in T_0 to 1.39 mm in T_{441}) in this treatment showed, after 441 days (Figure 6c,d). In all treatments, as well as in the uncompacted control, it was observed that the GMD was lower 441 days after the first evaluation, which can be ascribed to the sampling period. The second assessment was preceded by a long rain period (Figure 1), which probably reduced the aggregate resistance to defragmentation, even though the samples had been dried at room conditions prior to analysis.

The reduction of the GMD caused by compaction is harmful for the maintenance of the soil physical properties, since the water-stable aggregates were well correlated with the soil permeability and susceptibility to water erosion and indirectly indicate the soil structure quality (Silva et al., 2000).

The increase of the number of forwarder passes entailed a higher content of total organic C, mainly in the 0–5 cm layer, and of total N in the 5–10 cm layer, 441 days after compaction (Figure 7a,b). In fact, there was a reduction of the mineralization rate of the soil organic matter (SOM) during the 441 days after treatment application in the compacted soils, probably due to an increase of the physical protection of the SOM with soil compaction. However, there was no difference between the treatments in the load experiment (Figure 7c,d).

Compaction reduces the total soil porosity and alters pore size distribution, favoring a rise in the percentage of smaller pores, in which organic material can be physically protected from microbial action (Breland & Hansen, 1996).

There was a difference between the response models of C and N mineralization that can be ascribed to the occurrence of denitrification in pores whose diameter was reduced considerably by compaction, which leads to a decrease of the diffusion of oxygen (Renault & Stengel, 1994; Jensen et al., 1996). According to Breland & Hansen (1996) the reduction of the total volume of pores after compaction increases the

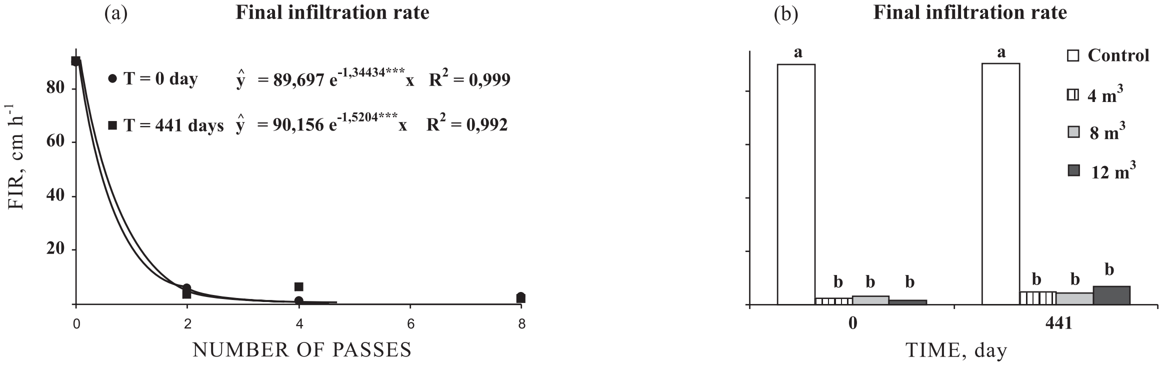

Figure 5. Final infiltration rate (FIR) of water in the soil as affected by the number of passes (a) and forwarder load (b) in eucalyptus stand after 0 and 441 days.

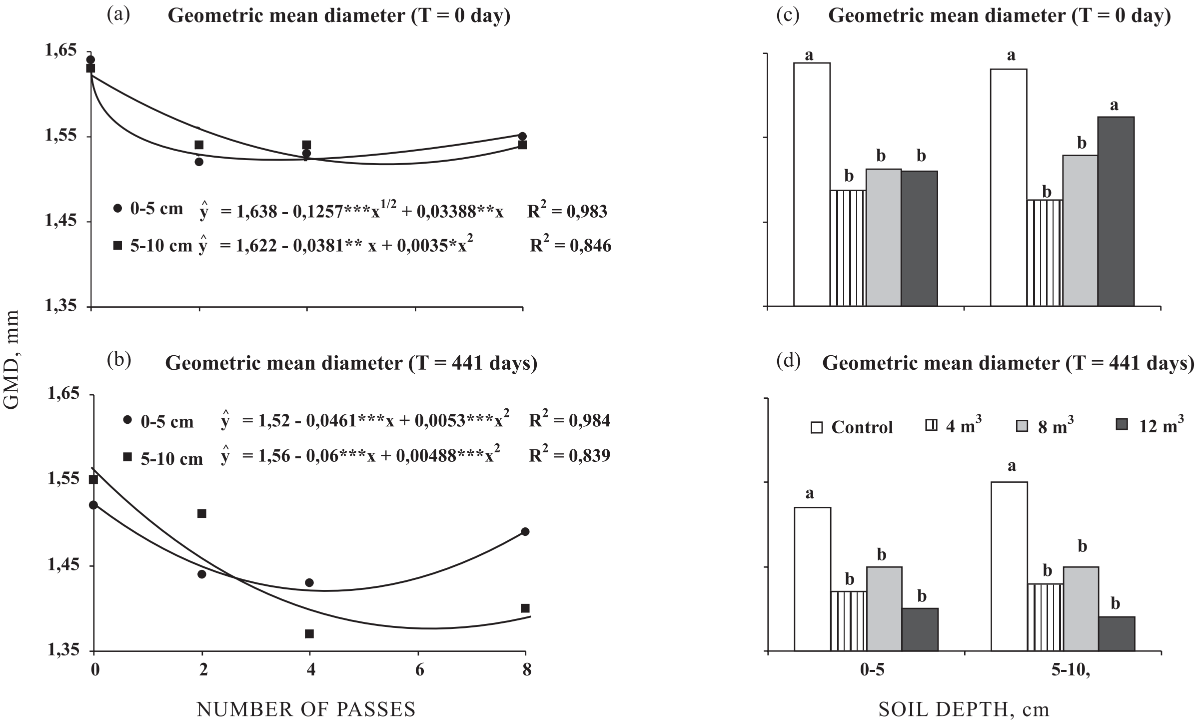

Figure 6. Geometric mean diameter (GMD) of water-stable aggregates as affected by the number of passes (a, b) and forwarder load (c, d) in eucalyptus stand after 0 and 441 days.

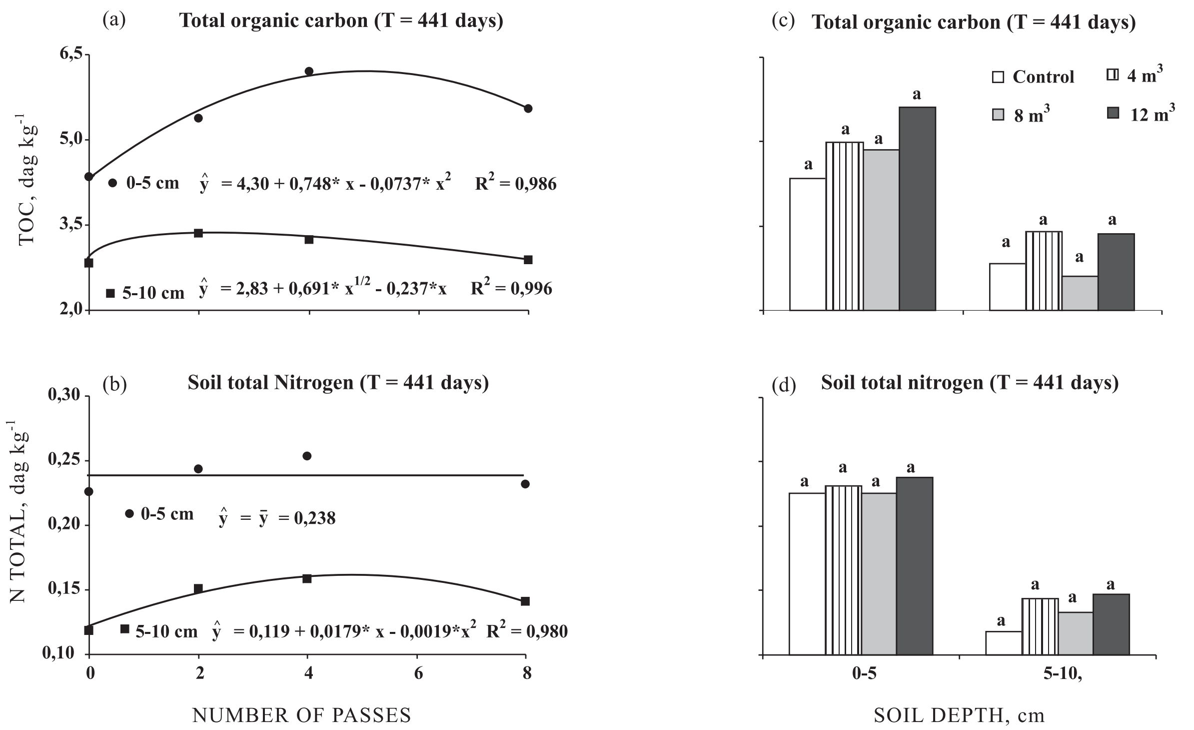

Figure 7. Total organic carbon and total nitrogen of the soil as affected by the number of passes (a, b) and forwarder load (c, d) in eucalyptus stand after 441 days.

probability of anaerobic conditions. This can largely inhibit the decomposition of organic material and increase gas losses of N through denitrification (Hansen et al., 1993).

There was no effect of the number of passes on the ammonium ($N\text{-}NH_4^+$) concentration in the soil 441 days after treatment application (Figure 8a). However, in the load experiment only the treatments with 4 and 12 m^3, at the depth of 5–10 cm, had a higher $N\text{-}NH_4^+$ concentration than the uncompacted control (Figure 8c).

Soil nitrate ($N\text{-}NO_3^-$) was reduced with the increment of the number of passes (Figure 8b). This reduction may have been caused by the compaction which favors anaerobic conditions and $N\text{-}NO_3^-$ losses through denitrification, a situation that occurs in the presence of NO_3^- in anaerobic microsites where the microbial O_2 demand exceeds the supply by diffusion (Arah & Smith, 1989; Adams & Akhtar, 1994). However, there was no difference between the treatments in the load experiment 441 days after the initial compaction (Figure 8d).

It was verified by Breland & Hansen (1996) that compaction did not affect the relative quantities of $N\text{-}NH_4^+$ and $N\text{-}NO_3^-$ in the soil, and they suggested that the reduction of soil aeration was not great enough to affect nitrification.

Of the measurements performed 406 days after planting, only diameter at breast height (DBH) had a quadratic response to the number of passes (Figure 9a,b,c). The treatments in the load experiment did not differ from each other (Figure 9d,e,f).

According to Greacen & Sands (1980) there is an optimum soil bulk density for tree growth, above or below which the yield sinks. According to these authors, the compaction effects on root growth may be result of complex interactions between soil penetration resistance, water and nutrient availability, and aeration.

This weak response to compaction can be attributed to the effect of the planting holes on tree root growth. To plant the eucalyptus seedlings, planting holes of 30 x 30 x 30 cm had been dug in the forwarder tracks, which probably enabled the root system to expand towards the region of adjacent uncompacted soil, making a full development of the plants possible. It is also known that the increase of soil penetration resistance can be restrictive to root growth above certain values that varied from 1.5 to 3.0 MPa, according to Grant & Lafond (1993), and from 2.0 to 4.0 MPa, according to Oussible et al. (1992) and Arshad et al. (1996). Since the maximum PR values were 2.36 and 2.02 MPa, respectively, in the 0–5 and 5–10 cm layers, with eight forwarder passes, and the rain intensity during the months prior to harvest was high, it is likely that the root system developed even into the regions of compact soil, since resistance to penetration decreases substantially with the increase of soil moisture.

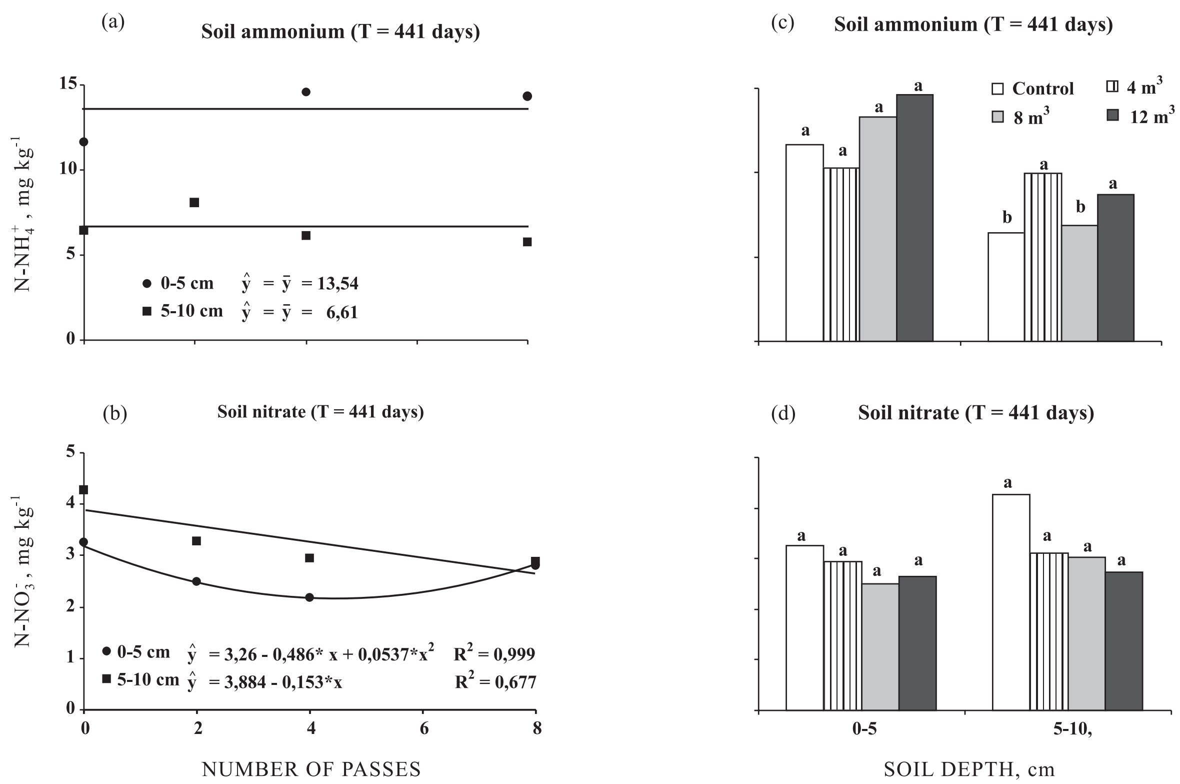

Figure 8. Soil ammonium and nitrate as affected by the number of passes (a, b) and forwarder load (c, d) in eucalyptus stand after 441 days.

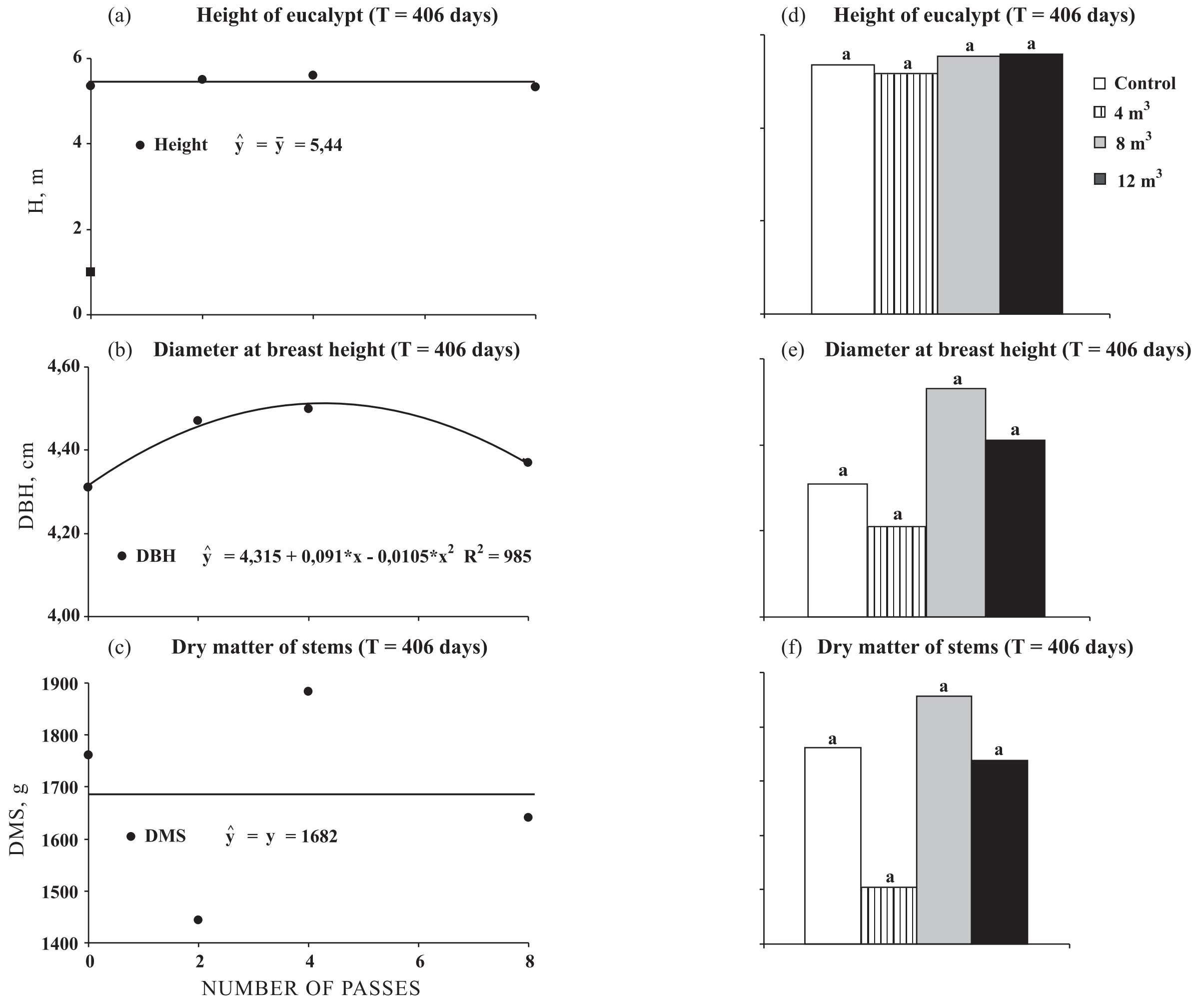

Figure 9. Height, diameter at breast height and dry matter of eucalypt stems grown for 406 days in soil exposed to different numbers of forwarder passes (a, b, c) and loads (d, e, f).

CONCLUSIONS

1. Forwarder traffic increased bulk density, microporosity, penetration resistance, total organic carbon, total nitrogen (only in the surface layer: 5–10 cm) and $N\text{-}NH_4^+$ (only in the layer of 5–10 cm, when the forwarder had 4 and 12 m^3 of wood in the load experiment); reduced the geometric mean diameter, total porosity, macroporosity, water infiltration and $N\text{-}NO_3^-$ in the soil. There was no effect of compaction on the stem dry matter yield and tree height.

2. Two forwarder passes accounted for the greatest part of the compaction effects.

3. The effects of compaction persisted for 441 days after forwarder traffic although there were signs of recovery of some soil properties.

4. The factor traffic intensity is weightier than load regarding increased soil compaction caused by the forwarder.

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