Soil Compaction on Forest Soils from Different Kinds of Tires and Tracks and Possibility of Accurate Estimate

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Abstract – Nacrtak

An 8-WD forwarder loaded with 9,520 kg of timber, and fitted with low or high tire pressures, or tires rounded with tracks, was repeatedly driven on soil for 1, 8 and 24 passes to investigate mechanistic influences on soil compaction. Soil compaction occurred during the early passes, and heavy compaction occurred after 8 passes. High pressure tires caused heavy compaction in the deeper soil layer zones. The compacted zone for a loaded forwarder with tracks was shallow in depth and had the lowest degree of compaction. Linear regression between contact pressure and average depth of ruts after 24 passes was derived. An increase in contact pressure of 100 kPa caused a decrease of 5.7% in soil porosity at 10–15 cm depth after 24 passes. Maximum increment of cone index of 85 kPa, which occurred at depths of 14 to 28 cm, meant a decrease of 1% soil porosity between depths of 10-15 cm. Additionally, ruts of 10 cm in depth decreased porosity by 7%. Tracks kept original porosity with lowest compaction and should therefore be useful for preventing soil compaction.

Key words: *soil compaction, tracks, depth of ruts, porosity*

1. Introduction – *Uvod*

Harvesting and regeneration management must be solved scientifically and technologically so as to ensure sustainable forestry. Soil compaction caused by harvesting operations can affect future regeneration and growth of trees. Therefore, different kinds of tracks, machine size and load, and frequency of passes of forwarder transport should be decided in advance to minimize compaction for specific soil types and operational conditions.

In this study, we intended to clarify differences of soil compaction among different kinds of tire pressures and tracks using the technique of cone-penetrometer. A cone-penetrometer has been used to measure soil compaction because it has quick application and can be used for interrelation of different soil conditions (Kumakura et al. 1993). The relationships between the increase of cone index and the decrease of soil porosity after harvesting by a forwarder/tractor have been shown to estimate soil compaction (Matangaran et al. 1999, 2006). Many results of soil compaction have been reported previously (Kozlowski 1999, Šušnjar et al. 2006), and they must be comparable by a standardized method such as cone index to provide an easy and accurate technique.

2. Methods and experimental site – *Metode i mjesto istraživanja*

Experimental site was selected at a recently harvested forest in the Grib Forest in North Zealand, Denmark. The site was nearly flat, but small changes of inclination were inevitable especially by the existence of roots and stumps (Fig. 1). Clear-cutting of planted Norway spruce (*Picea abies* (L.) Karst.) was done just before the experiment, and timber was extracted using a forwarder system. The surface was disturbed at random by low frequency of forestry vehicle passes, and slash was left in the form of leaves and branches.

Soil type at the experimental site was humus layer of 5 to 20 cm in depth, sandy A-layer of 15–30 cm thick, yellow-brownish soil of B-layer of 10–15 cm thick, and below this there was was gray clay C-layer. Soil moisture was about 60% at the surface,

Fig. 1 Experimental site and the experimented forwarder Rottne Rapid 8WD with tracks

Slika 1. *Mjesto istraživanja i istraživani forvarder Rottne Rapid 8WD s polugusjenicama*

35% in the inner part, and 20% in the deeper part. It was estimated and characterized as dry condition.

The forwarder used for experiment was Rottne Rapid 8-WD (Fig. 1). According to the catalogue, the unloaded total weight was 13,270 kg, the front part weigh was 7,980 kg and that of the rear part was 5,290 kg, and the loading capacity was 12,000 kg. The length, height, overall width, and width between outer side of the tires was 8,810 mm, 3,600 mm, 2,850 mm, and 2,650 mm, respectively. Tires were Trelleborg Twin 421 Mark II 600/55–26.5 16PR Forestry Steel Belt. Tracks were made of steel for the experiment by Eco Baltic manufacturing via Olofsfors AB, whose weight of one series for a pair of tires was 850 kg.

The experiment treatments were a forwarder with rubber wheels of low pressure of 120 kPa, high pressure of 350 kPa, and 500 kPa rounded with tracks, respectively. This corresponded to six treatments designed as unloaded and loaded. The load was set at 9,520 kg of logs as normal condition. In case of only wheels, two sets of tracks of 1,700 kg were loaded to reduce the difference of weight with tracks. The forwarder speed was 2.8 km per hour. Straight and nearly flat 18 courses of 20 m length were prepared before the movement of the forwarder, and three courses were randomly allotted for one treatment.

Contact area of high pressure tires on the soil at the experimental site was 60×45 cm (rear) and 55×32 cm (front), and that of low pressure tires was 70×55 cm (rear) and 50×50 cm (front). Net contact area of one series of tracks was approximately 8,033 cm^2 on hard ground, and 8,940 cm^2 on soft ground, which was measured from footprint of track shoes, respectively. Contact pressure of each treatment was estimated from these contact areas (Table 1).

After 1, 8 and 24 passes of a running forwarder, cone index was measured at the center of each of the ruts (Fig. 2). Five samples were randomly selected to

Table 1 Contact pressure of forwarder on soil per axles

Tablica 1. *Dodirni tlak forvardera na tlo po osovinama*

Treatment *Djelovanje*	Front axle *Prednja osovina*	Rear axle *Stražnja osovina*
	10^5 Pa	10^5 Pa
Low pressure tires – unloaded *Gume s niskim tlakom (neopterećen forvarder)*	0.78	0.45
Low pressure tires – loaded *Gume s niskim tlakom (opterećen forvarder)*	0.88	0.99
High pressure tires – unloaded *Gume s visokim tlakom (neopterećen forvarder)*	1.11	0.63
High pressure tires – loaded *Gume s visokim tlakom (opterećen forvarder)*	1.25	1.41
Tracks – unloaded *Polugusjenice (neopterećen forvarder)*	0.07	0.05
Tracks – loaded *Polugusjenice (opterećen forvarder)*	0.07	0.11

Fig. 2 Ruts from loaded high pressure tires after 23 passes

Slika 2. *Kolotrazi nakon 23 prolaska opterećenih gumama s visokim tlakom* the right and left of each rut center, respectively. Cone index at the center line between right and left ruts was measured at 5 points for comparison to the control. It was assumed that the cone index between ruts was the same as that outside the courses because the inner distance between ruts was 150 cm, which had enough distance available for identifying and locating unaffected soil. Also, 20 points outside the courses were measured for the control. Depth of ruts from the original surface of 10 points along a course was also measured to the right and left of each rut after 24 passes. Most woody debris and humus layer on the surface of ruts disappeared after 24 passes.

A cone-penetrometer used for the measurement of soil compaction corresponded to the American Society of Agricultural Engineering standard, according to the manufacturer Findlay, Irvine Ltd. The cone diameter was 12.83 mm. Cone resistance force (kgf) of various depths from 3.5 to 52.5 cm at an inerval of 3.5 cm was measured, but almost all measurements were disturbed by stones or roots. Cone index (100 kPa) was converted to the cone resistance (kgf) after multiplying each indexed value by 0.762.

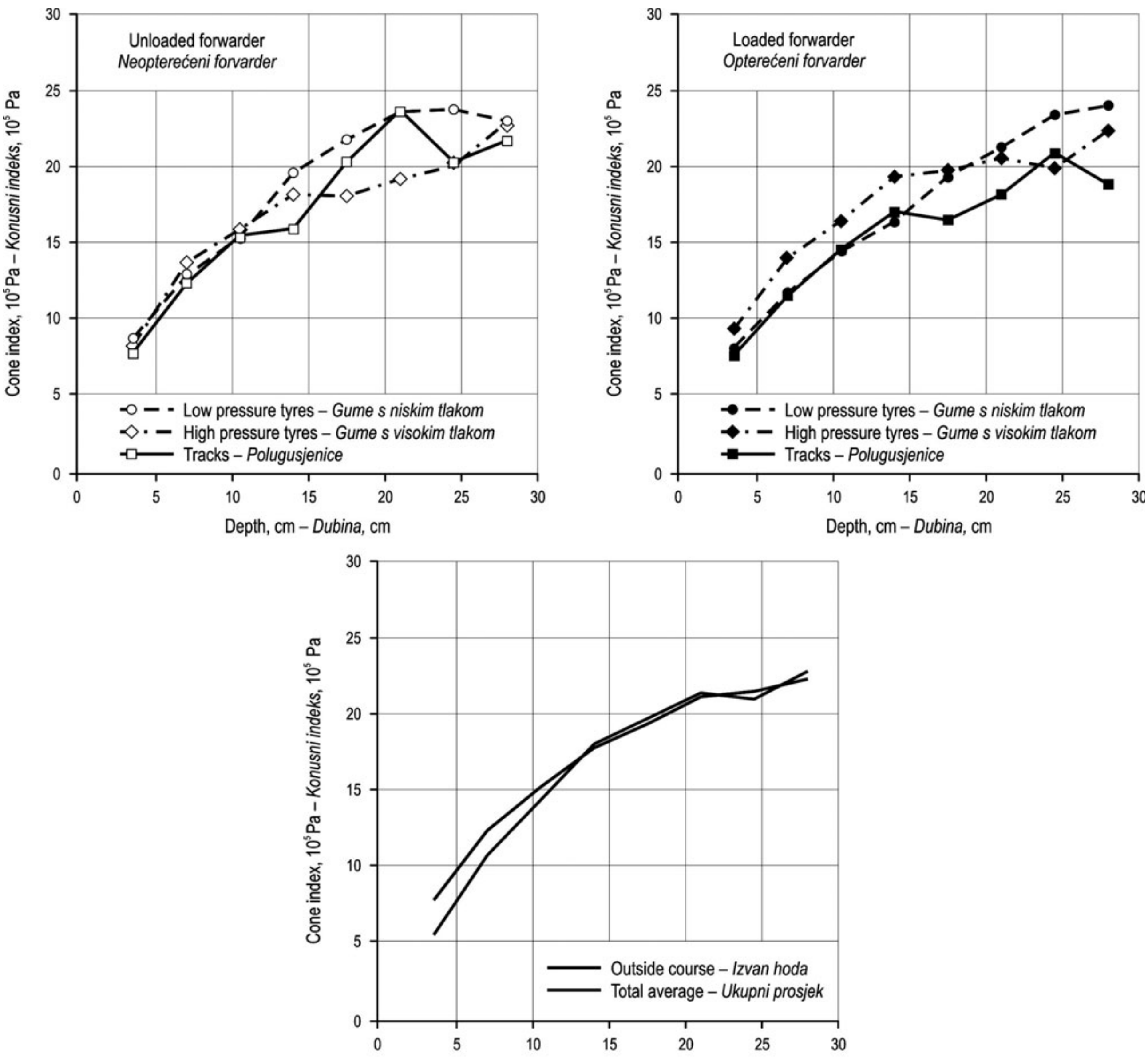

Fig. 3 Average cone index before experiment

Slika 3. *Prosječni konusni indeks tla prije istraživanja*

Soil samples were extracted after 24 passes of each treatment and the control outside the course by using soil sampler of 10^{-4} m^3 at the surface and at the layer of 10–15 cm at the depth below the humus, which represented the most compacted zone. Three samples were taken for each treatment at each depth interval. Soil porosity was analyzed according to JIS test method (Japanese Society of Soil Mechanics and Foundation Engineering 1969).

3. Soil cone index of the experimental site – *Konusni indeks tla na mjestu istraživanja*

There were numerous stones and roots with stumps in the underground. Data of cone index varied with increasing underground depth. Although the cone index outside the course from the surface to a depth of 10.5 cm was lower than the average one for 18 courses before applying treatments, the result of F-test among 18 courses and outside the course showed no significant differences ($p > 0.05$). The average cone index also showed similar values (Fig. 3). There were no significant differences among the averages of the six treatments and outside the course after F-test ($p > 0.05$).

At 3.5 to 14 cm in depth, soil layer had thick humus and the cone index was stable, and from 14 to 31.5 cm the soil had sandy layer with a cone index that ranged over 500 kPa. From about 31.5 cm in depth, the layer became yellow-brownish clay, corresponding to a wider index range. A regression line for the total value was based on 110 measurements that had 18 courses and 20 points outside the course. This was therefore considered to be representative value of the cone index for the experimental site before soil compaction by forwarder, and thus could be used as the control for pre-treatment.

4. Resarch results – *Rezultati istraživanja*

4.1 Soil compaction – *Zbijanje tla*

It was observed that the tires pushed surface soils downward even on a slightly downward sloping surface, and on these surfaces increased compression of soils was recorded. In the case of loaded treatments, increases of cone index were apparent with increased number of passes (Fig. 4). The range of lines was small at the zone between the surface around 14 cm in depth. The difference increased remarkably from the depth of more than 14 cm with the number of passes. The depth between about 14 and 21 cm was the most compacted zone. Under the depth of nearly 35 cm, data did not show any distinct trends. Cone indices at 14 to 21 cm in depth by loaded low and high pressure tires, and fitted tracks after 24 passes were 2210–2390 kPa, 2350–2670 kPa, and 2100 kPa, respectively. Fitted tracks had the lowest compressed soil, whereas high pressure tires had the greatest.

For the case of unloaded low pressure tires, cone index increased with increasing number of passes, and the maximum cone index after 24 passes was between 2250–2350 kPa, which was the same for the loaded treatment, whereas lines of unloaded high pressure tires and tracks were lower than those of the loaded treatments. However, depth of compacted zone for unloaded low pressure tires was about 3.5 cm shallower than the loaded treatment. For unloaded high pressure tires, although no passes had higher values, cone index increased with the number of passes. The increased cone index after 24 passes was 2250 kPa at 17.5 cm in depth, which was nearly the same as that by unloaded low pressure tires, but depth of compacted zone was around 3.5 cm deeper than unloaded low pressure tires. The lines after unloaded tracks were the lowest among all treatments, although the cone index after passes was lower than that of no passes because of low compaction.

Although there were minus values probably due to the almost negligible difference compared to the average value, the average increment of cone index from the decided value of control with no passes was evident after the repetition of the passes (Fig. 5). The strong compaction occurred at the earliest stage of passes of loaded high pressure tires. Low pressure tires and tracks with and without load showed increased cone index at the surface, and at deeper layers, increase of cone index became smaller for both unloaded and loaded tracks. In the case of unloaded high pressure, the increase of cone index became also smaller with increasing depth of soil. Loaded low pressure tires and tracks showed high values of compaction from eighth passes onwards. Similarly, with unloaded low pressure tires and tracks compaction occurred after eight passes.

In the range from the surface to 28 cm in depth, the maximum increment of the cone index was evident from the value of the control and its depth (Table 2). Differences of the increment of cone index between loaded and unloaded low pressure tires were small, whereas the increment of cone index of loaded high pressure tires and tracks were larger than that for unloaded condition. For unloaded treatments, the maximum increment of low and high pressure tires occurred at 3.5 to 24.5 cm in depth, whereas for tracks it occurred at 3.5 cm. On soil treated with loaded low pressure tires, high pressure tires, and tracks, depth of the maximum increment

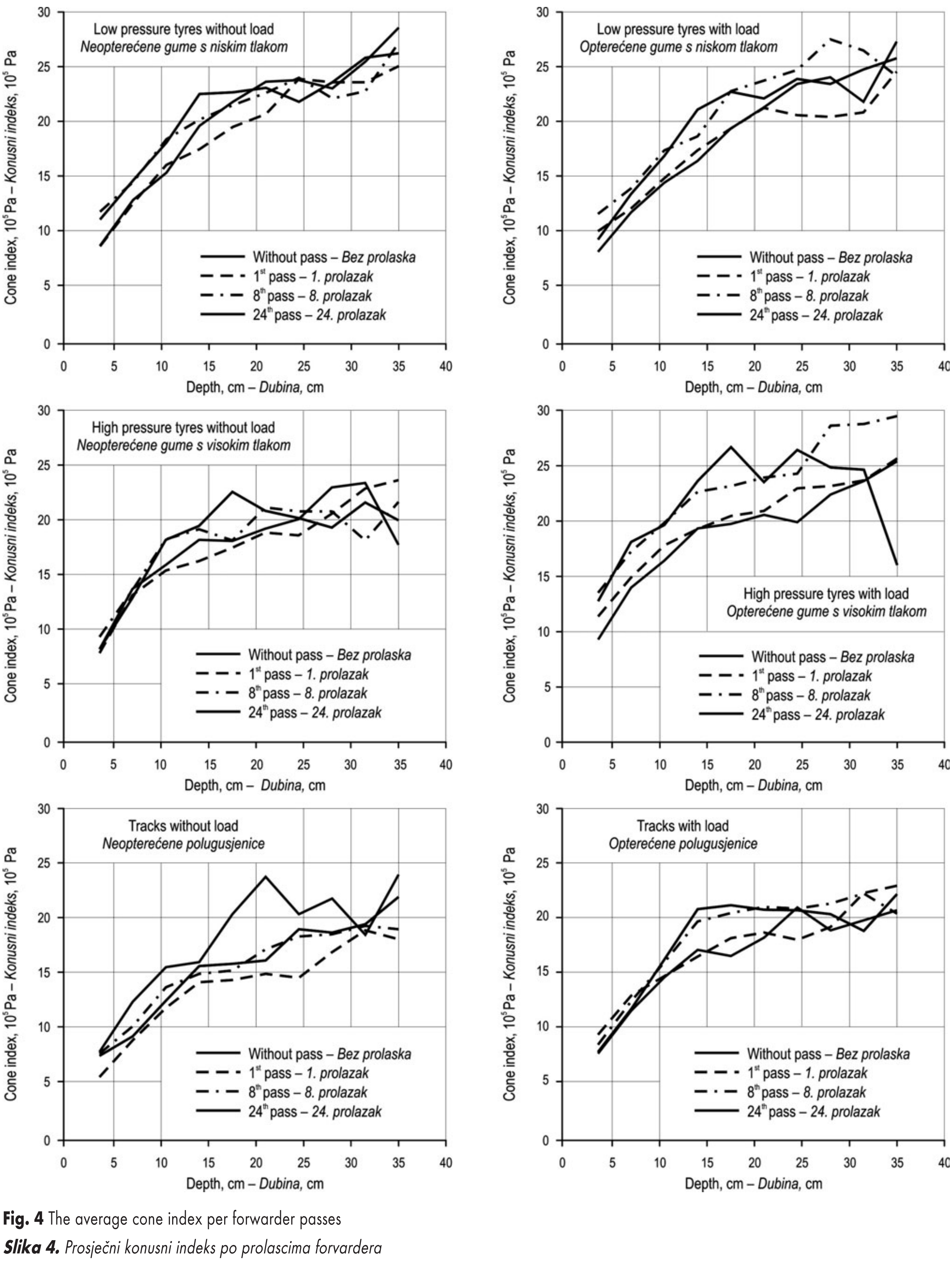

Fig. 4 The average cone index per forwarder passes

Slika 4. *Prosječni konusni indeks po prolascima forvardera*

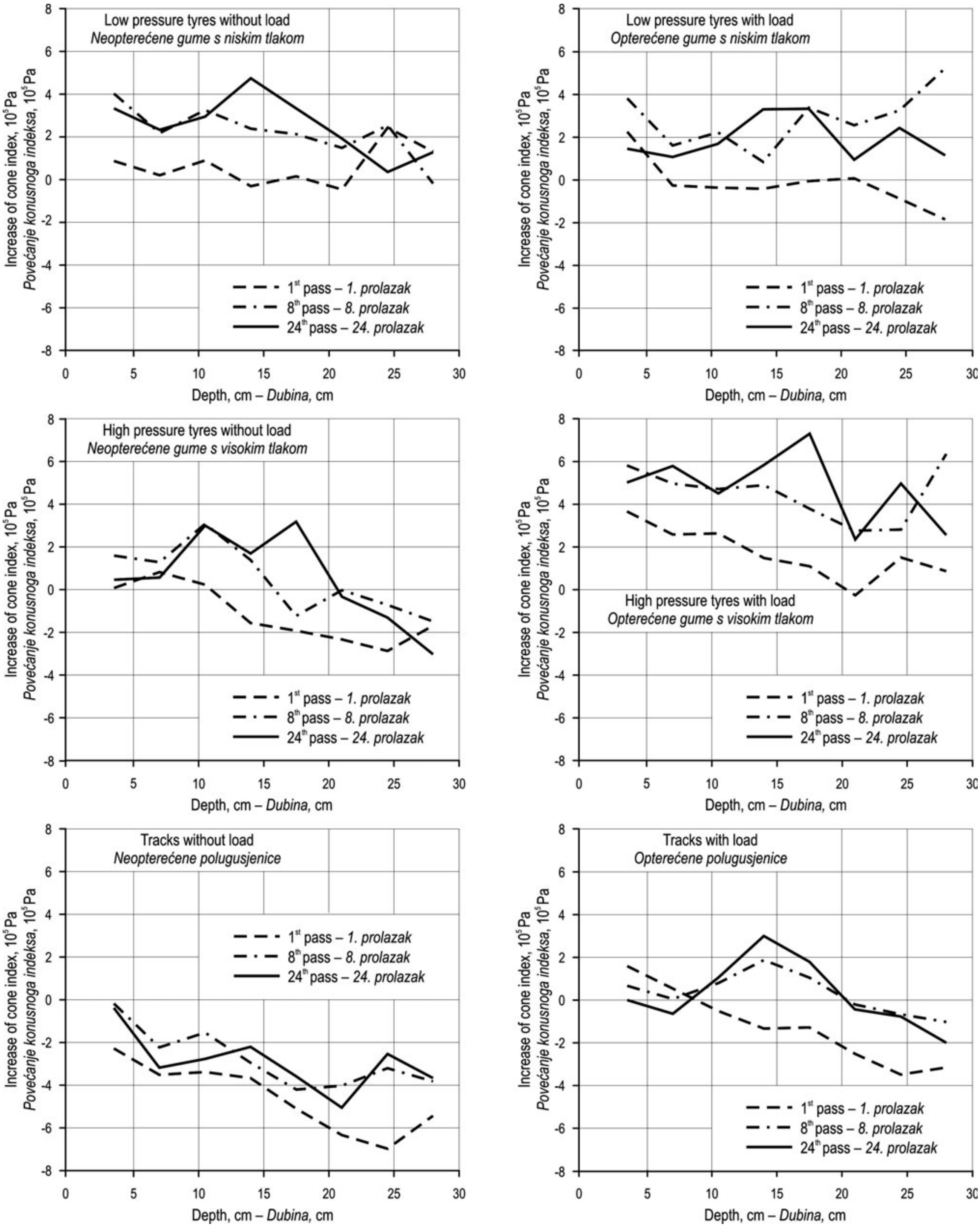

Fig. 5 The increment of cone index from none passes

Slika 5. *Povećanje konusnoga indeksa u odnosu na neizgaženo tlo*

Table 2 Maximum increment of the cone index (10^5 Pa) and its depth after treatments

Tablica 2. *Najveće povećanje konusnoga indeksa (10^5 Pa) i dubina mjerenja nakon prolazaka forvardera*

Passes *Prolasci*	Low pressure tires unloaded *Gume s niskim tlakom (neopter. forvarder)*	Low pressure tires loaded *Gume s niskim tlakom (opterećen forvarder)*	High pressure tires unloaded *Gume s visokim tlakom (neopter. forvarder)*	High pressure tires loaded *Gume s visokim tlakom (opterećen forvarder)*	Tracks – unloaded *Polugusjenice (neopter. forvarder)*	Tracks – loaded Polugusjenice (opterećen forvarder)
1	0.9 (10.5 cm)	2.3 (3.5 cm)	0.8 (7.0 cm)	3.7 (3.5 cm)	–2.3 (3.5 cm)	1.6 (3.5 cm)
2	2.9 (17.5 cm)	1.9 (3.5 cm)	1.3 (3.5 cm)	5.4 (3.5 cm)	–1.8 (3.5 cm)	1.6 (3.5 cm)
4	3.3 (17.5 cm)	2.8 (3.5 cm)	1.1 (7.0 cm)	5.3 (10.5 cm)	–1.3 (3.5 cm)	1.3 (3.5 cm)
8	4.0 (3.5 cm)	5.2 (28.0 cm)	3.1 (10.5 cm)	5.8 (3.5 cm)	–0.2 (3.5 cm)	1.9 (14.0 cm)
16	3.7 (17.5 cm)	2.3 (14.0 cm)	1.1 (10.5 cm)	6.2 (24.5 cm)	–0.7 (3.5 cm)	2.0 (14.0 cm)
24	4.7 (14.0 cm)	3.3 (17.5 cm)	3.2 (17.5 cm)	7.3 (17.5 cm)	–0.4 (3.5 cm)	3.0 (14.0 cm)

was found to be 28, 28, and 14 cm, respectively. Loaded low and high pressure tires had compaction at deeper soil layers, and the maximum increment of cone index reached 524 kPa after eight passes and 732 kPa after 24 passes, respectively. The compaction of loaded tracks was smaller and occurred at shallower depths compared to the other treatments.

The maximum increment of cone index was derived (Fig. 6). Soil compaction occurred in the early passes (Shishiuchi and Adachi 1982). About 200 to 400 kPa of cone index increment occurred in the first pass and those of loaded low and high pressure tires reached at 317 and 532 kPa after four passes, respectively. The severe compaction was caused by loaded high pressure tires. The line of loaded tracks existed between those of unloaded low and high pressure tires. There were differences of compacted soil depth and the maximum increment of cone index between four and more than eight passes for all treatments. The relationship between contact pressure and maximum increment of cone index after 24 passes showed a tendency that increased contact pressure resulted in increasing compaction (Fig. 7).

4.2 Depth of ruts – *Dubina kolotraga*

The depth of ruts was shallow for the low frequency passes. Once ruts were formed, repetition of passes made the ruts deeper. The observations endorsed the differences on the increase of ruts between four passes and more than eight passes on the

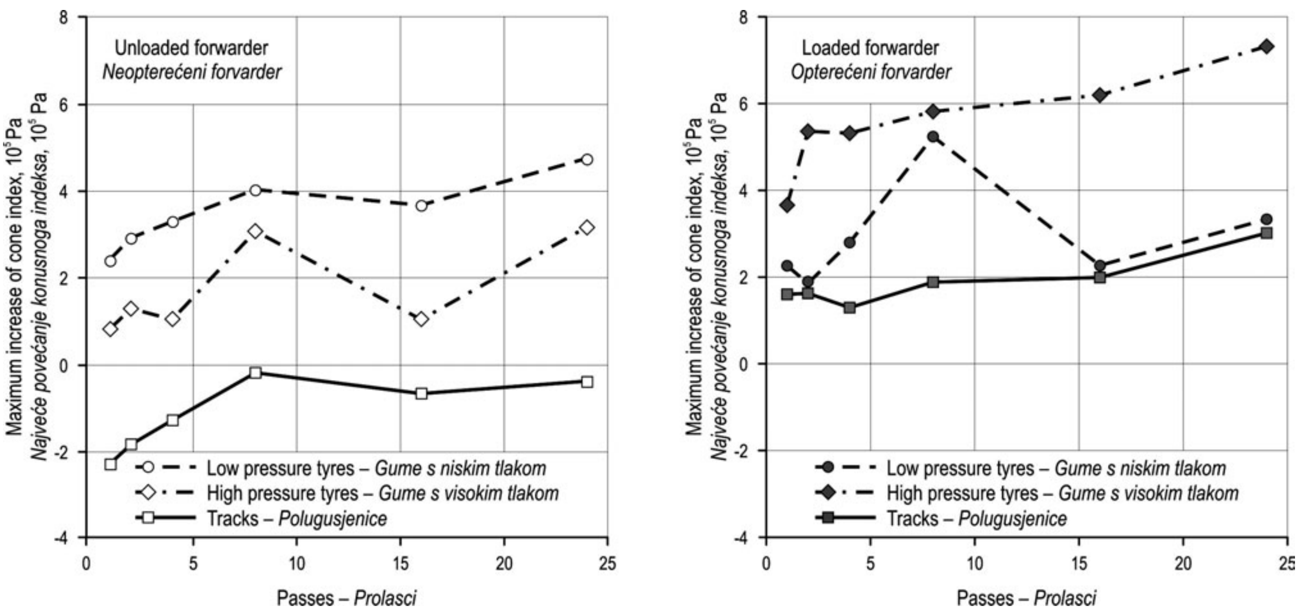

Fig. 6 Maximum increment of cone index

Slika 6. *Najveće povećanje konusnoga indeksa*

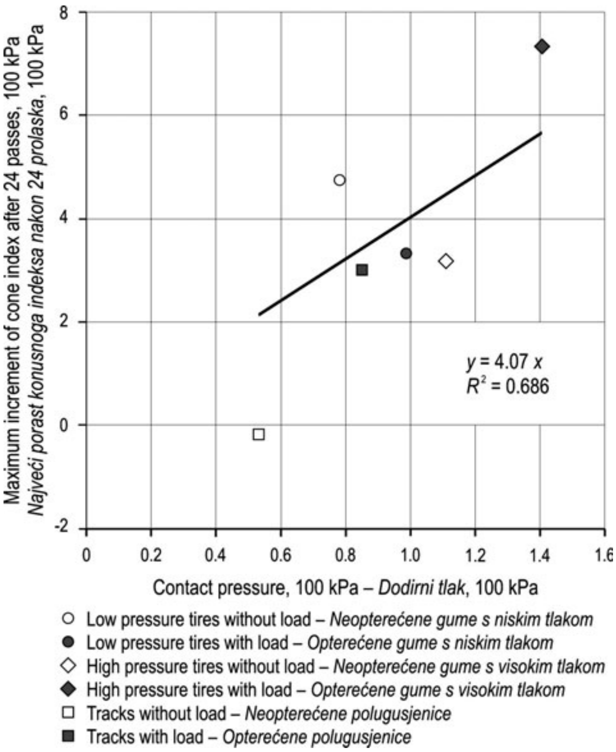

Fig. 7 Maximum increment of cone index vs. contact pressure after 24 passes

Slika 7. *Ovisnost najvećega povećanja konusnoga indeksa o dodirnom tlaku na tlo nakon 24 prolaska*

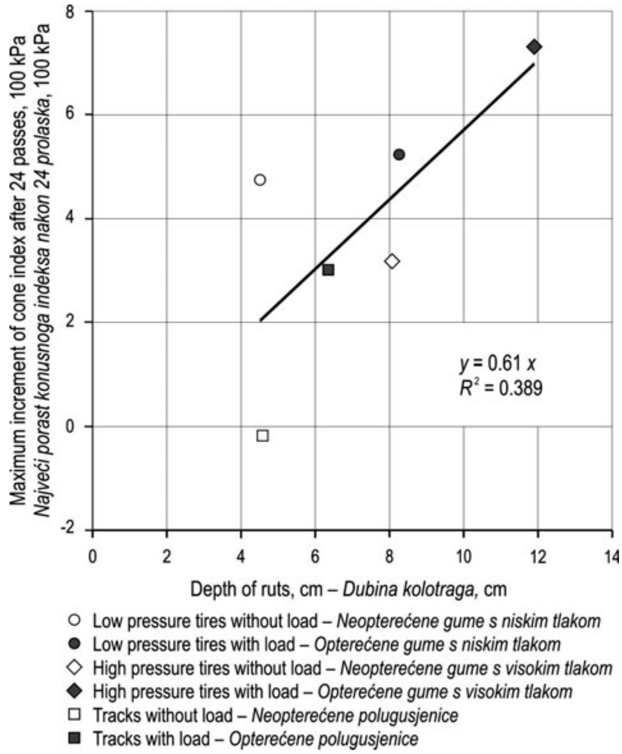

Fig. 8 Maximum increment of cone index vs. depth of ruts after 24 passes

Slika 8. *Ovisnost najvećega povećanja konusnoga indeksa o dubini kolotraga nakon 24 prolaska*

maximum increment of cone index. When the forwarder moved over a stump or on a small downward slope, sudden increases of load pressure caused increased compression followed by shearing forces that accelerated the forming of ruts.

A tendency was recorded that the deeper ruts were more compacted at some depths of soil (Fig. 8), but significant correlation coefficient between the average depth of ruts after 24 passes and maximum increment of cone index was not obtained. The treatments of high pressure tires unloaded and loaded, and loaded low pressure tires had deep ruts. Depth of ruts by unloaded low pressure tires and tracks was shallow and the same at about 4.5 cm, but the compaction by low pressure tires was much higher than that caused by tracks. For the loaded low pressure tires and tracks, maximum increment of cone index of tracks was lower than that of low pressure tires, and the depth of ruts by tracks was about 2 cm shallower than that by low pressure tires. Although thus the physical mechanism of compaction and forming of ruts was different between tires and tracks, linear relationship between contact pressure and average depth of ruts after 24 passes was obtained ($p < 0.01$) (Fig. 9).

4.3 Physical soil properties – *Fizikalne značajke tla*

The average specific gravity of the soil surface was 2.37 g/cm^3 (Table 3), and there were no significant differences among treatments by F-test ($p > 0.05$). Inner part of soil at the depth of 10–15 cm was 2.48 g/cm^3, and there were no significant differences among treatments ($p > 0.05$). Between the average 2.37 g/cm^3 and 2.48 g/cm^3, a significant difference was found by t-test ($0.01 < p < 0.05$). The inner part of soil of loaded high pressure tires had the most compacted soil, and the decrease of liquid and air phases from no passes after 24 passes were both about 5% (Table 3).

The correlation coefficient (r) between soil bulk density and porosity of 24 samples was 0.987 ($p < 0.05$). A derived line showed theoretically the point of soil porosity of 100% for zero of bulk density and the point of the average specific gravity of 2.43 of all samples (Fig. 10). Porosity of the inner soil was considered as the most compacted zone, and smaller than that of the surface. There were no significant differences among porosities of the four treatments

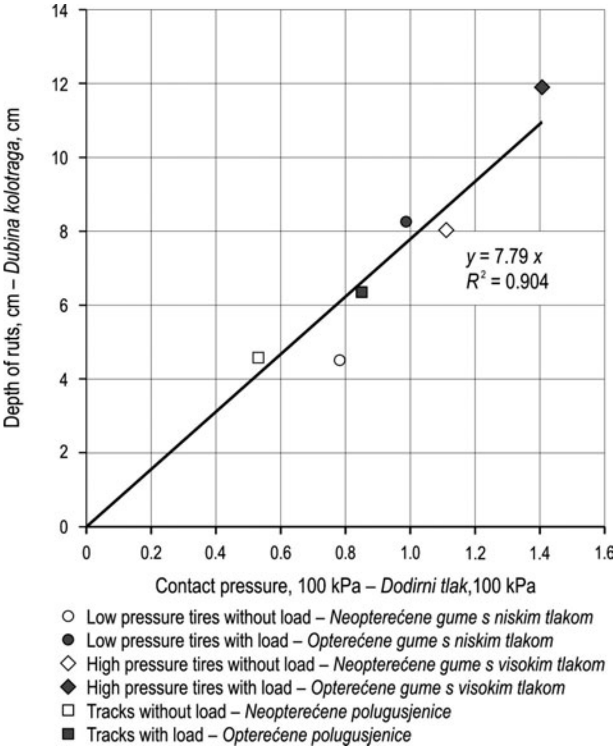

Fig. 9 Depth of ruts vs. contact pressure after 24 passes

Slika 9. *Ovisnost dubine kolotraga o dodirnom tlaku na tlo nakon 24 prolaska*

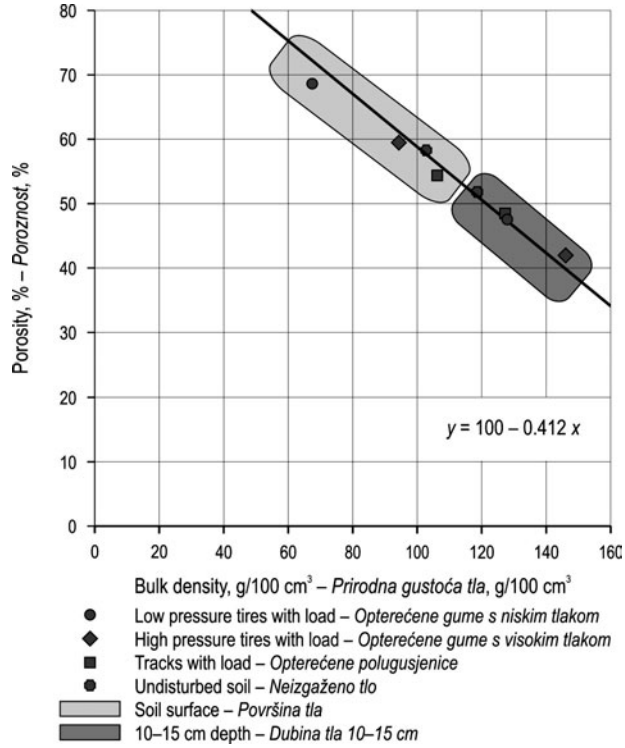

Fig. 10 Soil porosity vs. bulk density

Slika 10. *Ovisnost poroznosti o prirodnoj gustoći tla*

at the surface soil by F-test ($p > 0.05$). However, a significant difference was recorded between loaded low and high pressure tires at the surface soil ($p < 0.05$). At the inner soil, there were no significant differences between loaded high and low pressure tires, and among loaded low pressure tires, tracks and no passes by t-tests ($p > 0.05$). But there was a significant difference between loaded high pressure tires and tracks ($p < 0.01$). Loaded high pressure tires had the highest value of compaction for the inner soil, and porosity decreased by nearly 10% from the treatment with no passes. Tracks sustained soil porosity better than other treatments, as the clear relationship between contact pressure and soil porosity

Table 3 Physical properties of soil samples after treatments with loaded forwarder

Tablica 3. *Fizikalna svojstva uzoraka tla nakon prolazaka opterećenog forvardera*

Part *Dio tla*	Treatment *Djelovanje*	Spec. gravity *Spec. gustoća tla*	Bulk density *Prir. gustoća tla*	Solid phase *Čvrsta faza*	Liquid phase *Tekuća faza*	Air phase *Zračna faza*	Porosity *Poroznost*
		g/cm^3		%			
Surface *Površina*	No passes – *Bez prolaska*	2.50	102.8	41.7	43.8	14.5	58.3
	Low pressure tires – *Gume s niskim tlakom*	2.28	67.4	31.4	64.4	4.0	68.6
	High pressure tires – *Gume s visokim tlakom*	2.36	94.3	40.5	50.8	8.7	59.5
	Tracks – *Polugusjenice*	2.33	106.2	45.6	45.6	8.8	54.4
Inner *Unutrašnjost*	No passes – *Bez prolaska*	2.48	118.6	48.2	35.0	16.8	51.8
	Low pressure tires – *Gume s niskim tlakom*	2.46	127.9	52.5	35.4	12.1	47.5
	High pressure tires – *Gume s visokim tlakom*	2.52	146.0	58.1	29.7	12.2	41.9
	Tracks – *Polugusjenice*	2.48	127.3	51.5	40.9	7.6	48.5

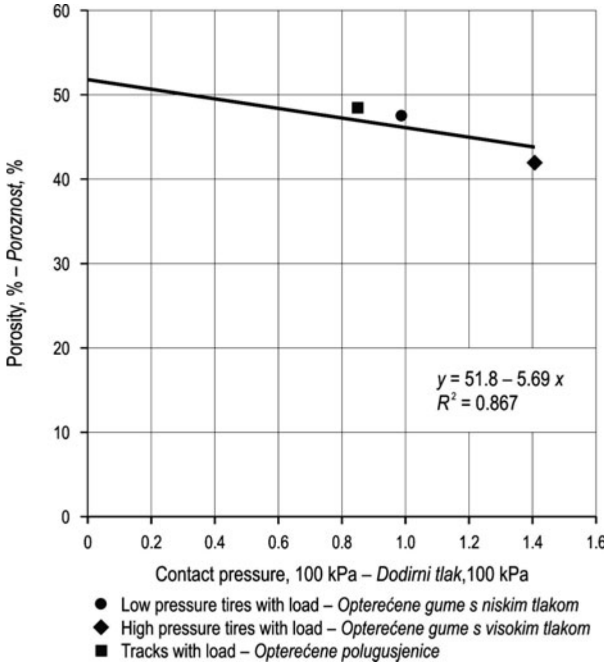

Fig. 11 Soil porosity in the inner part vs. contact pressure after 24 passes

Slika 11. *Ovisnost poroznosti tla na dubini 10-15 cm o dodirnom tlaku nakon 24 prolaska*

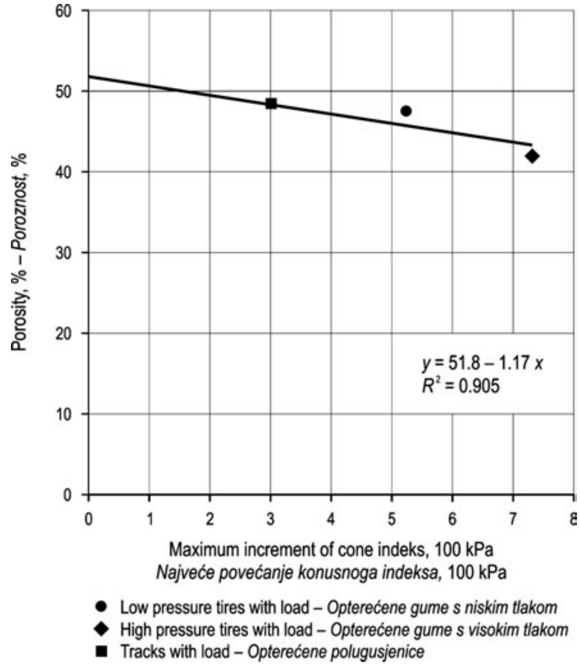

Fig. 12 Soil porosity vs. maximum increment of cone index after 24 passes

Slika 12. *Ovisnost poroznosti tla o najvećem povećanju konusnoga indeksa nakon 24 prolaska*

in the inner part was nearly linear ($0.01 < p < 0.05$) (Fig. 11). The increment of 100 kPa in the contact pressure caused the decrease of 5.7% porosity at 10–15 cm in depth. Although the most compacted depth was different among treatments, relationship between the maximum increment of cone index, which occurred at 14 cm to 28 cm in depth, and porosity was nearly linear ($p < 0.05$) (Fig. 12). The increase of cone index of 85 kPa equaled a decrease of soil porosity of 1%.

4.4 Estimation of soil compaction – *Procjena zbijanja tla*

The formation of ruts differed between tires and tracks, and it was related to the contact pressure of tire/track surfaces to the soil matrix. The ruts of 10 cm in depth showed a tendency of decrease of 7% in soil porosity at 10–15 cm in depth ($p < 0.05$) (Fig. 13). It was recognized that the ruts caused by loaded tracks were the shallowest and any decrease of porosity was the smallest after 24 passes.

5. Conclusions with discussion – *Zaključci s raspravom*

The underground soil conditions varied greatly especially in deeper soil layers because the samples for cone index decreased by disturbance of rocks or roots. The range of fluctuation was small in the zone between the surface and about 14 cm in depth because of a rapid increase of cone index in the thick

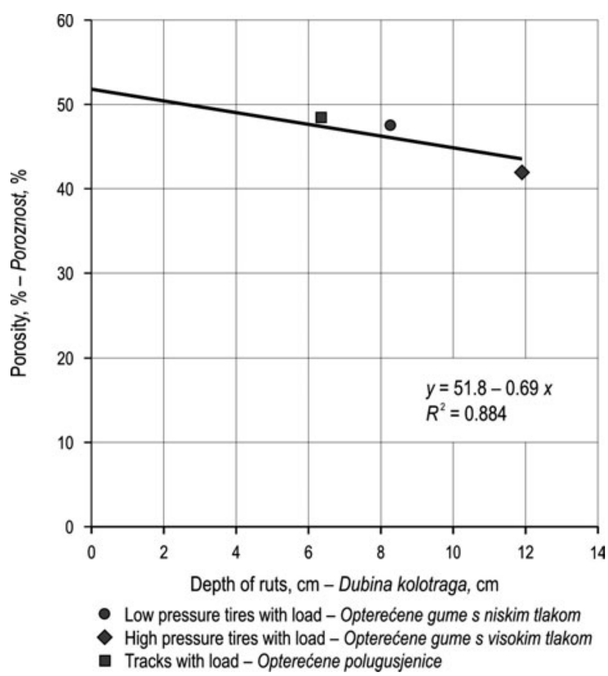

Fig. 13 Soil porosity vs. depth of ruts

Slika 13. *Ovisnost poroznosti tla o dubini kolotraga* homogeneous humus layers. The heavy compaction occurred in the sandy zone from 17.5 to 24.5 cm in depth on the hard layer of clay occurred after eight passes. Additionally, increment of cone index of tracks loaded and unloaded was smaller than those of tires.

Soil compaction occurred in the early passes. Loaded treatments caused about 200 to 400 kPa of increment of cone index in the first pass. The results show that this increment of cone index of 200 kPa equaled a decrease of 2.6% of soil porosity.

As the physical mechanism of compaction by surface-to-surface movement and forming ruts was different between tires and tracks, most compacted depth of soil was different among treatments. Rut depths were not significantly affected by tire pressures but they increased significantly with the number of two and five machine passes, and soil density increased significantly with increasing number of forwarder passages (Eliasson 2005). The regression line of contact pressure and the average depth of ruts were obtained, as well as contact pressure and maximum increment of cone index after 24 passes. Furthermore, regressed line of contact pressure to depth of ruts should be used to predict the depth of ruts from large forwarders.

The significant difference between loaded low and high pressure tires at the surface part might be related to the difference of the increment of cone index. Loaded low pressure tires after 24 passes showed the increment of cone index at the surface soil of 150 kPa, and the maximum increment of cone index, which was 333 kPa, occurring between14 to 17.5 cm. On the contrary, loaded high pressure tires after 24 passes showed the increment of cone index at the surface part at 500 kPa, and the maximum increment of cone index of 732 kPa occurred at the deeper part of 17.5 cm compared to low pressure tires. Results for loaded high pressure tires that had the greatest maximum increment of cone index in the deeper soil zones suggested stronger physical forces influencing the soil than other treatments.

Tracks could reduce rut depth by up to 40% and cone index by about 10% compared to wide and soft tires in spite of the increased mass of tracks by 10–12% (Bygdén et al. 2003). In our experiment, maximum increment of cone index of loaded low pressure tires and tracks was small after the first few passes, and both values could have been similar if the influence of added weight of tracks with wheels was eliminated. However over eight passes, the compaction by loaded low pressure tires increased deeper in the soil layers. Maximum increment of cone index of loaded tracks was lower than that of loaded low pressure tires, and the depth of ruts by loaded tracks was smaller than that by loaded low pressure tires by about 20% after 24 passes. It was recognized that high pressure tires were not practical, and that tracks were the best alternative.

Advanced logging machines have been shown to increase soil bulk density and decrease both the total soil porosity and the water-holding capacity of the soil (Kamaruzaman 1991). According to our results, the ruts of 10 cm in depth meant the decrease of soil porosity of 7% in the inner part. It will, therefore, be possible to predict soil compaction only by the depth of ruts. The compacted zone caused by tracks was shallow and near the surface is showed low compaction. Tracks therefore sustained the original pre--treatment porosity of the soil. This is advantageous for the growth of plants because porosity is highly correlated to the growth and vigor of plants when nourishment is sufficient, and because undersurface soil is left undisturbed and roots are active within 10 cm in depth for absorbing nutrients and water (Shishiuchi and Adachi 1982). Compaction in the deeper zone means prolonged influence on the soils.

However, according to the above results, tracks will be excellent and useful for preventing soil compaction for soft and sensitive ground.

It is necessary to choose the direction of forwarding to avoid repetitions of the same course resulting in heavy soil compaction that indirectly avoids erosion, and to utilize strip roads. It was observed that the surface of compacted ruts was wet, and the water accumulated as a result of decreased porosity after compaction. Once soil was compacted, it would take several years to recover its non-disturbed physical soil properties, especially organic matter (Shishiuchi and Satomura 1995). Site preparations such as scarifying after harvesting operations will be needed before plantation or for the success of natural regeneration. The results can, therefore, be used for determining and indentifying the most appropriate harvesting systems, frequency of passes, route location, and sustainable forestry. In the future, recovery term of soil porosity, and quantity of lost nutrition due to soil compaction should be further clarified.

Acknowledgement – *Zahvala*

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6. References – *Literatura*

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Sažetak

Zbijanje šumskoga tla različitim tipovima guma i polugusjenica te mogućnost dovoljno precizne procjene

Cilj je ovoga rada utvrditi razlike u zbijanju tla pri višekratnim prolascima forvardera. 8-kotačni forvarder je tijekom istraživanja bio opremljen gumama s niskim tlakom punjenja, gumama s visokim tlakom punjenja te polugusjenicama (slika 1). Na osnovi dimenzija guma i polugusjenica te raspodjele opterećenja po osovinama forvardera izračunati su dodirni tlakovi kotača osovine na tlo (tablica 1). Pri kretanju opterećenoga i neopterećnoga forvardera na sječini bilježili su se prolasci na ispitnim izvoznim pravcima (slika 2). Nakon 1, 8. i 24. prolaska mjereno je zbijanje tla konusnim penetrometrom i dubina kolotraga te uzimani uzorci tla u nenarušenom stanju na dubini tla 10–15 cm radi laboratorijskoga određivanja poroznosti tla, prirodne i specifične gustoće tla. Zbijanje je tla određeno temeljem razlike konusnoga indeksa tla na izvoznom smjeru nakon prolazaka forvardera te konusnoga indeksa neizgaženoga tla (slike 3 do 7).

Opterećeni je forvarder u prvom prolasku uzrokovao povećanje konusnoga indeksa tla od 200 do 400 kPa ovisno o primjeni različitih guma ili polugusjenica. Najveće je povećanje zbijanja tla uočeno nakon osmoga prolaska forvardera.

Primjena je guma s visokim tlakom uzrokovala veće zbijanje tla u dubljim slojevima. Povećanje konusnoga indeksa tla te dubina zbijanja tla po prolascima forvardera bila je najmanja pri primjeni polugusjenica. U odnosu na primjenu guma s niskim tlakom dubina je kolotraga za 20 % manja pri primjeni polugusjenica.

Na dubinu kolotraga utječe ponajprije broj prolazaka forvardera, te je određena ovisnost dubine kolotraga o povećanju konusnoga indeksa tla i o dodirnom tlaku kotača na tlo (slika 8 i 9).

Kretanje forvardera opremljenoga gumama s visokim tlakom uzrokovalo je najveće smanjenje poroznosti tla – za 10 %, dok su najmanje promjene u poroznosti tla uočene pri kretanju forvardera s polugusjenicama (slika 11 i 12). Povećanje dodirnoga tlaka kotača forvardera na tlo za 100 kPa uzrokuje smanjenje poroznosti tla za 5,7 % na dubini 10–15 cm.

Nastanak se kolotraga razlikuje s obzirom na primjenu različitih tipova guma i polugusjenica. Ustanovljena je ovisnost poroznosti tla o dubini kolotraga te je uočeno da se kod kolotraga dubine 10 cm poroznost tla smanjuje za 7 % (slika 13). Iz navedenoga se zaključuje da je jednostavnim mjerenjem dubine kolotraga moguće procijeniti stupanj zbijanja tla.

Na osnovi tih rezultata zaključuje se da polugusjenice treba primjenjivati na slabonosivim tlima radi sprečavanja oštećivanja šumskoga tla.

Ključne riječi: *zbijanje tla, polugusjenice, dubina kolotraga, poroznost tla*

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