Effects of Rubber-Tired Cable Skidder on Soil Compaction in Hyrcanian Forest

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Abstract – Nacrtak

The use of skidders equipped with rubber tires is a well accepted practice for the extraction of timber from the forest, but the application also causes considerable environmental problems. The aim of the study was to evaluate the effects of different slope gradient, number of machine passes on skid trails and soil depth on soil compaction. The study was designed as an experiment with the factors including slope gradient, soil moisture, and soil depth on various skid trails and with different number of machine passes. The effects of four slope classes (flat, 10%, -10% and -20%), three soil depth classes (5, 15 and 25 cm), and different compaction levels based on various number of machine passes (0, 1, 5, 8, 10, 15, 20, 25 and 30) were evaluated. A Timberjack cable skidder was used and the study location was in the Kheyrud Educational and Research Forest located in the Hyrcanian forest in northern Iran. The increased number of machine passes increased soil bulk density, but the highest rate of compaction occurred after the initial few passes. Uphill skidding increases soil compaction more than downhill skidding. The increases in bulk density were still significant at the maximum sampling depth of 20–30 cm. Soil bulk densities at 5, 15 and 25 cm depth averaged 35, 22 and 17% higher than densities of undisturbed soil.

Keywords: soil compaction, soil bulk density, rubber-tired cable skidder, Hyrcanian forest.

1. Introduction – *Uvod*

Forest soils, in general, are susceptible to compaction as they are loose with high organic-matter, and are generally low in bulk density, high in porosity, and low in strength (Froehlich et al. 1985; Kolkaa and Smidt 2004). The impact of skidding operations on forest soils can be divided into three major categories: soil profile disturbance, soil compaction and soil puddling and rutting (Rab et al. 2005).

When a mechanical load is applied to the soil, soil particles are rearranged closer together resulting in increased bulk density (mass per unit volume) (Cullen 1991; Eliasson 2005; Grace et al. 2006), reduction of the total porosity associated with a reduction of macropores (Gayoso and Iroume 1991; Gomez et al. 2002; Ares et al. 2005), increase in soil strength; except for soil with low bearing capacities (Horn et al. 1994), decreased infiltration capacity (Horn et al. 1994, 2004), decreased gaseous exchange and soil aeration (Horn et al. 1994), an increase in resistance to penetration (Ampoorter et al. 2007), decrease in saturated hydraulic conductivity (Greacen and Sands 1980; Horn et al. 1994; Grace et al. 2006), and increased micropore proportion (Kolkaa and Smidt 2004). One of the major impacts of harvesting operations is soil profile disturbance. Soil disturbance is usually defined in terms of mixing and/or removal of litter and soil, which may change the physical, chemical or biological properties of soil (Rab et al. 2005). Depending on the equipment used, the surface soils are variously mixed, buried or inverted.

During timber harvesting the degree of soil compaction depends on various factors including: site and soil characteristics (Adams and Froehlich 1984; Ampoorter et al. 2007) such as soil texture (Froese 2004; Rohand et al. 2004), soil moisture (Johnson et al. 2007), the number of machine passes (Eliasson 2005; Šušnjar et al. 2006; Ampoorter et al. 2007; Eliasson and Wasterlund 2007; Wang et al. 2007) and harvesting system. In addition, the machine characteristics affecting the degree of soil compaction include type of machine (Šušnjar et al. 2006; Wang et al. 2007), mass of vehicle and load (Rab 1996; Saarilahti 2002; Šušnjar et al. 2006; Horn et al. 2007), type, number of wheels and inflation pressure of the tires (Ziesak 2006), amount of logging slash (Wronski and Murphy 1994; Eliasson and Wasterlund 2007). A couple of studies reported by several researchers show that one of the critical factors affecting the degree of soil compaction is the number of machine passes over a specific point. These studies show that most compaction occurs during the first ten passes of a vehicle with the most occurring in the first three passes. Subsequent passes generally have little additional effect (Ampoorter et al. 2007). Most compaction occurred after the initial few passes (Matangaran and Kobayashi 1999), but bulk density also increased significantly after more than 3 passes (Gayoso and Iroume 1991; Eliasson 2005; Eliasson and Wasterlund 2007). Matangaran and Kobayashi (1999) found that the bulk density increased markedly by the first and second pass of the tractor, but did not change after the fifth pass.

Few studies have documented slope gradient of trail effects (longitudinal and transversal slope of trail) on the extent and degree of soil compaction and disturbance. Krag et al. (1986) showed that during timber harvesting, slope steepness had a stronger effect than season of logging on soil disturbance. Under steep terrain conditions, the machine slipped continuously and remained in a given place for a longer period of time, puddling and dragging the soil (Gayoso and Iroume 1991). Sidle and Drlica (1981) found that the slope did not significantly affect bulk density, but they concluded that it can be an important factor in the potential level of compaction. Jamshidi et al. (2008) found that there was no detectable difference in compaction between machine skidding on flat trails and trails with longitudinal gradient or transversal slope. Compacted layers are often found at different soil depths. However, the deeper layers of many soils are compacted further after a few passes. The values of the soil bulk density mostly depend on the quantity of organic matter. In the surface horizons, the soil bulk density is low, and as with the increase of depth, organic matter is rapidly decreased, the bulk density increases in subsoil (Froehlich and McNabb 1984). Increases in organic matter reduce soil compactibility (Kozlowski 1999). A strong increase in bulk density is most distinct in the upper 20 cm of the soil, since the exerted pressure is maximal at the soil surface and declines with increasing depth as the total pressure is spread out over an enlarging area (Gent and Morris 1986; Ampoorter et al. 2007). Johnson et al. (2007) noted that soil compaction was generally limited to skid trails and top soil layers (<30 cm). Eliasson and Wasterlund (2007) reported that an increased number of machine passages increased soil dry density in the upper 20 cm.

The Hyrcanian mountainous forest in northern Iran is rich in biological diversity, with endemic and endangered species, and a diverse range of economic and social conditions. In the Hyrcanian forest, a few studies have been carried out about the effects of forest operations on soil compaction and bulk density. Jamshidi et al. (2008) measured the changes in bulk density in the top 10 cm of soil following machine and animal skidding in the Hyrcanian forest. They found that the average soil bulk density in the tracks of machine skid trails was significantly greater than the soil density outside the tracks, but the increase in bulk density was not significant on the animal trails.

The extent of the severe disturbance from ground-based harvesting systems varies depending on slope and steep terrain, although the effects of slope on soil disturbance and bulk density have received less attention. The specific objectives were to: quantify the extent of trail area and winching line (disturbance area) throughout the harvest unit, to characterize and establish the threshold levels for the machine traffic with respect to bulk density and slope gradient or direction of skidding for three different soil depths.

2. Materials and methods – *Materijal i metode*

2.1 Study site – *Područje istraživanja*

About 65% of the Hyrcanian forests are located in mountainous areas with terrain slope of more than 27% (Fig. 1), where forest lands are not readily acces-

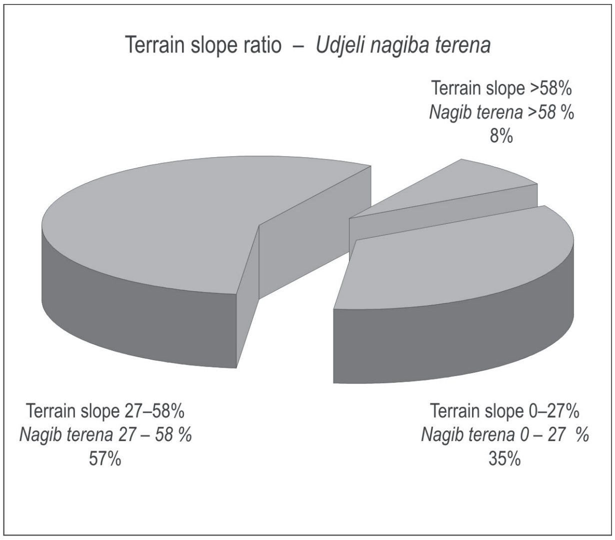

Fig. 1 Proportion of the Hyrcanian forest area based on terrain slope

Slika 1. *Udio nagiba terena šumskih zemljišta Hirkanijske šume (Golestan)*

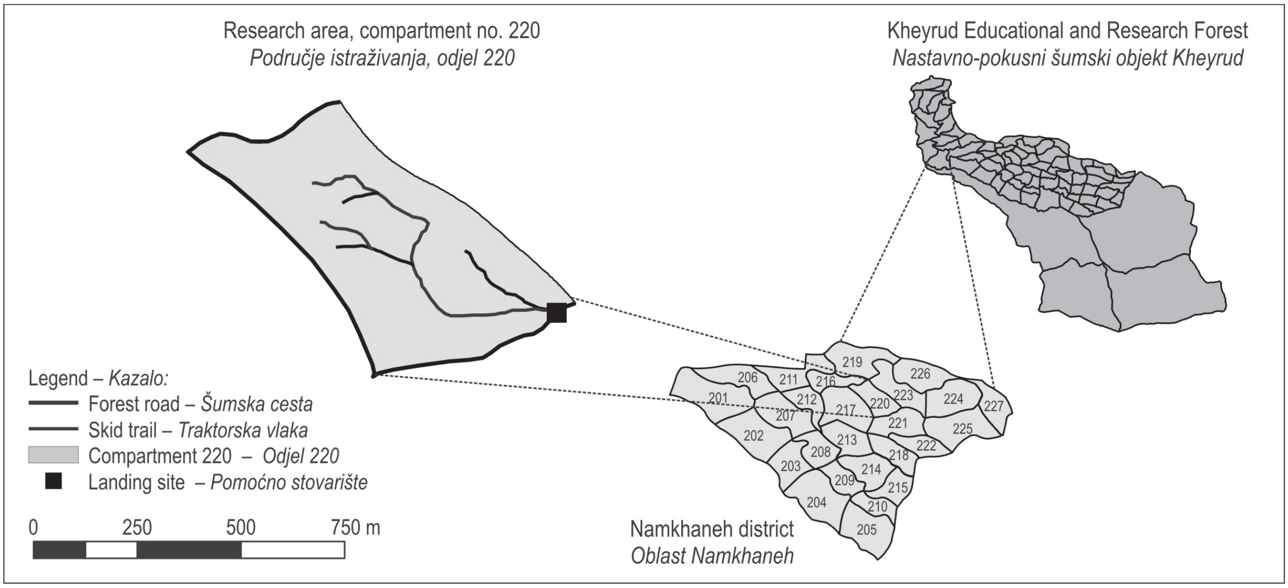

Fig. 2 Location of study site within the Hyrcanian Forest
Slika 2. *Područje istraživanja*

sible with ground-based logging equipments. The cable yarding technologies are still undeveloped in this forest area.

The research was carried out in compartment No. 220, which is located in Namkhaneh District within Kheyrud Educational and Research Forest in the Hyrcanian forest of northern Iran (Fig. 2). The altitude ranges from 1000 to 1135 m and the forest lies on a southwestern aspect. The average rainfall ranges from 1420 to 1530 mm/year, with the heaviest precipitation occurring in the summer and fall. The average daily temperature ranges from a few degrees below 0°C in December, January, and February, and up to +25°C during the summer. This area is dominated by natural forests containing native mixed deciduous tree species such as *Fagus orientalis* Lipsky, *Carpinus betulus* L., *Acer velutinum* Boiss. and *Alnus subcordata*. The management method is mixed un-even aged high forest with single and group selective cutting regime. The soil of the study site is classified as a brown forest soil (*Alfisols*) and well-drained. The texture of the soil ranges from silt loam to loamy.

Trees to be removed were felled, limbed and topped motor-manually. Felled trees were bucked and processed with chainsaws into logs, sawn-lumber and pulpwood. The logs of 5–15 meter length were extracted by rubber-tired skidders to the roadside landings. The fuel wood was extracted by mules. Also, in steep terrain that could not be reached by skidders, logs were processed to sawn-lumber and then hauled by mules. An important strategy is to limit traffic on designated skid trails, hence, landings and skid trails were clearly flagged on the ground before harvesting. The intension was to require the skidder to stay on the skid trail and winch logs on the trail. Downhill and uphill skidding to the landing was planned without any excavation and the skidding operations were done on natural ground. The extraction distances to the roadside landing was 780 m. The skid trail slope ranges from 0 to 35%. Table 1 presents some characteristics of the study site.

Table 1 Characteristics of the study site
Tablica 1. *Značajke istraživanoga područja*

Area, ha *Površina,* ha	Tree per ha *Broj stabala po ha*	Volume, m^3/ha *Obujam*, m^3/ha	Total removed trees *Ukupno posječeno stabala*	Total volume of removed trees, m^3 *Ukupni drvni obujam,* m^3	DBH of removed trees, cm *Raspon prsnih promjera posječenih stabala,* cm
17	173	504	270 (10 tree/ha – *10* stabala/ha*)*	872.3 (32 m^3/ha)	20–135

2.2 Experimental design and data collection
Plan istraživanja

Felling of marked trees was carried out in March and skidding operations were done in August 2008. At the time of harvesting, weather conditions were very dry and warm for more than 5 weeks and these conditions remained constant during skidding operations. Fig. 3 presents the 4WD Timberjack 450C rubber-tired skidder used in the study. This machine is normally an articulated, four-wheel-drive vehicle weighing 10.3 ton (55% on the front and 45% on the rear axle) with engine power of 177 hp (132 kW) and engine model of 6BTA5.9. It is equipped with a blade for light pushing of obstacles and stacking of logs. The skidder was fitted with 24.5–32 tires inflated to 220 kPa on both front and rear axles, and it had a ground clearance of approximately 0.6 m with overall width of 3.1 m. Timber bunching was carried out by the winch installed in the rear part of the skidder from the stump to the skidder and one end of the round wood was dragged on the ground. In the study areas, the average logged volume in each pass was 3.5 cubic meters (1 and 3 logs, respectively).

Twelve sampling transects were selected at different slope gradients along the designated skid trail for bulk density measurements (Fig. 4). Organic horizons were removed from the soil surface prior to density measurements, so that depth readings were referenced to the mineral soil surface. In order to ensure that the measurements were made in the same place after a certain number of passes, we have put the painted sticks in the center of skid trails. The painted sticks indicated the centers of the experimental skid trails at the skid trial, so that the machines would follow the same tracks at subsequent passes. Before skidding, four slope gradients were established in the skid trail with 3 replications in disturbed areas at 0–10 cm soil profile depth, and the different levels of compaction were applied by varying the levels of machine traffic: 0 (undisturbed), 1, 5, 8, 10, 15, 20, 25 and 30 machine passes. A pass implies a drive back and forth the selected trail. Four slope gradients of skid trail were 0 (flat trail), 10%, –10% and –20%. Also, prior to any skidding operations and after 20 machine passes, bulk density was measured at this four slope gradient trail (flat trail, 10%, –10% and –20%) at the 5 cm, 15 cm and 25 cm soil profile depths in wheel rut (A and B) and control sample point (Fig. 4) on the adjacent skid trail

Fig. 3 Timberjack skidder, equipped with rubber-tires while extracting timber

Slika 3. *Skider Timberjack prilikom privlačenja drva*

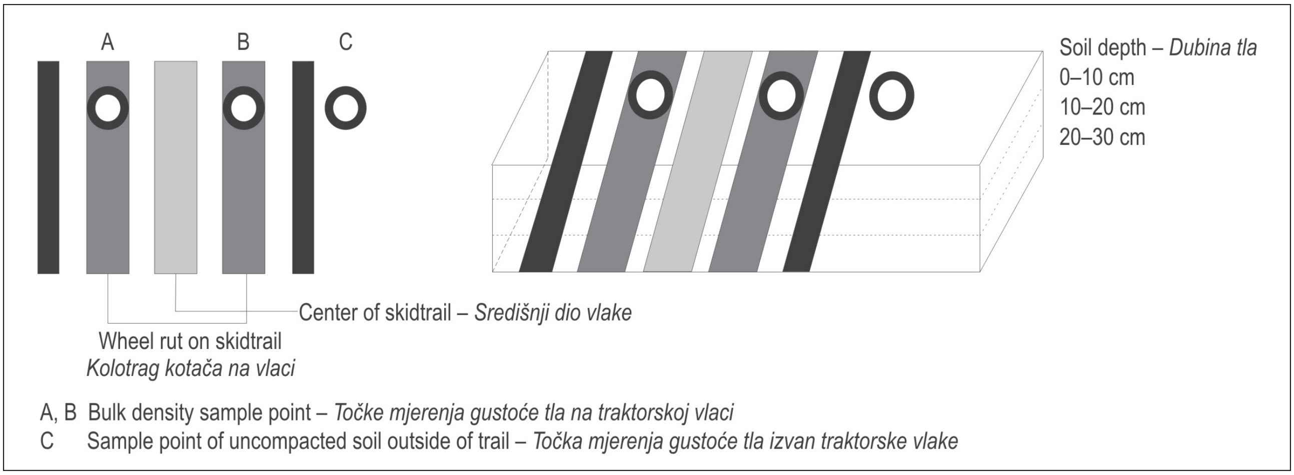

Fig. 4 Sketch of study layout for soil sampling

Slika 4. *Shema rada za uzimanje uzoraka tla*

(C). The soil sample cores were obtained from the layers of the mineral soil using a thin walled steel cylinder, 40 mm long and 56 mm in diameter, inserted into the soil by a hammer-driven device. After extracting the steel cylinder from the soil with minimal disturbance to the contents, the soil cores were trimmed flush with the cylinder end and extruded into a plastic bag for transporting it to the laboratory. Samples were weighed on the day they were collected and again after oven drying at 105 °C for 24 h to determine water content and bulk density.

In order to determine the extent of disturbance from skidder operations, disturbed widths were measured at 25 m intervals along the skid trails. Skid trail soil disturbance was classed as: A-horizon puddled and mixed with forest floor organic debris, and some A-horizon removed and the rest mixed with B-horizon. Also landing areas were measured in the compartment. Log winching, however, cause the excavation of the line between stumps near the vehicle, hence, for determining this displacement, total length and width of winching lines in both sides of trails were measured.

2.3 Statistical analysis – *Statistička obrada podataka*

The experimental design was a factorial arrangement of treatments conducted in a completely randomized design. General linear modeling (GLM) was applied to relate bulk density and rut depth to machine passes, slope gradient, and depth in relation to the skid trails. Post-hoc comparison of means was performed using Duncan's multiple designs to mean-based grouping with a 95% confidence level. Analysis of variance of the data was conducted in SPSS (release 15.0) to identify differences between bulk density values of four slope gradients in skid trails. Treatment effects were considered significant if $P<0.05$. Soil bulk density before and after skidding operations was compared using independent samples t-test. Also, one-way ANOVA was performed.

3. Results – *Rezultati*

3.1 Soil disturbance – *Oštećenje tla*

A detailed survey of the harvested unit following extraction with a cable skidder indicated that 5.8% of the total area (17 ha) was covered with skid trails and an additional 0.8% of the unit was occupied by the landing (Table 2).

In this study, ground-based winching of timber from the felling site to the skidder had substantial effect on soil displacement that occupied 0.9% of the total area. With the whole load lying on the ground, during winching it removed and pushed a layer of soil in front of itself. Finally, in this study 7.5% of the harvesting total area was disturbed and compacted. The disturbance width of the trail was significantly influenced by transversal slope gradients of trails. Therefore, the higher transversal slope, the wider is the trail width. There were three main skid trails in the harvest area with a total length of 1971 meters. The average

Table 2 Compartment disturbance area due to rubber-tired skidder operation

Tablica 2. *Oštećenje tla nastalo pri radu skidera*

Factor *Mjesto*	Trail length, m *Duljina vlake,* m	Trail average width, m *Prosječna širina vlake,* m	Disturbed area, m^2 *Oštećena površina tla,* m^2	Landing area, m^2 *Pomoćno stovarište,* m^2	Winching line, m *Duljina privitlavanja,* m	Line width, m *Širina traga privitlavanja,* m	Winching disturbed area, m^2 *Površina tla oštećena skupljanjem drva,* m^2	Total disturbed area, m^2 *Ukupno oštećena površina tla,* m^2
Trail 1 *Vlaka 1*	324	4.8	1555.2	1150	241	0.32	77.12	–
Trail 2 *Vlaka 2*	1387	5.1	7073.7	–	3752	0.34	1275.68	–
Trail 3 *Vlaka 3*	260	4.95	1287	180	380	0.29	110.2	–
Total area *Uk. površina*	1971	–	9916	1330	4373	–	1463	12709
Area, % *Površina,* %	–	–	5.8	0. 8	–	–	0.9	7.5

was 5 meters, and so occupied 5.8% of the total area. 4373 meters of winch line disturbance was recorded with an average width of 0.315 meters for a total of 0.9% of the area.

3.2 Soil compaction: influence of slopes and machine passes – *Zbijanje tla: utjecaj nagiba terena i broja prolazaka vozila*

Table 3 shows the analysis of the soil bulk density data influenced by machine passes and slope gradient for the cable skidder. The results showed that machine passes and slope gradient, and the interaction effects of machine passes × slope gradient were all significant variables ($P<0.05$).

Table 3 Analysis of variance (ANOVA) for the effect of number of machine passes (NP) and slope gradient (SG) on bulk density in 0–10 cm soil depth

Tablica 3. *Analiza varijance za prolazak vozila (NP) i nagib terena (SG) na dubini tla do 10 cm*

Source *Izvor podataka*	Sum of Square *Zbroj kvadrata*	df	Mean Square *Srednja kvadratna vrijednost*	*F*-value *F vrijednost*	*P*-value *P vrijednost*
NP	1.77	8	0.221	829.34	0.00
SG	0.17	3	0.058	216.36	0.00
NP × GS	0.06	24	0.003	9.67	0.00

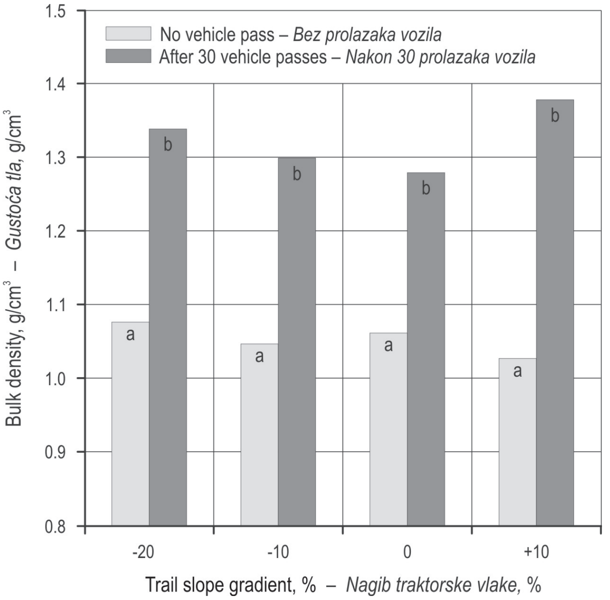

Fig. 5 Average bulk density (a) and its relative changes before and after skidding in each slope gradient of the trail and by independent samples *t*-test and Duncan's test (b)

Slika 5. *Prosječne vrijednosti (a) i relativne promjene gustoće tla nakon privlačenja drva (b)*

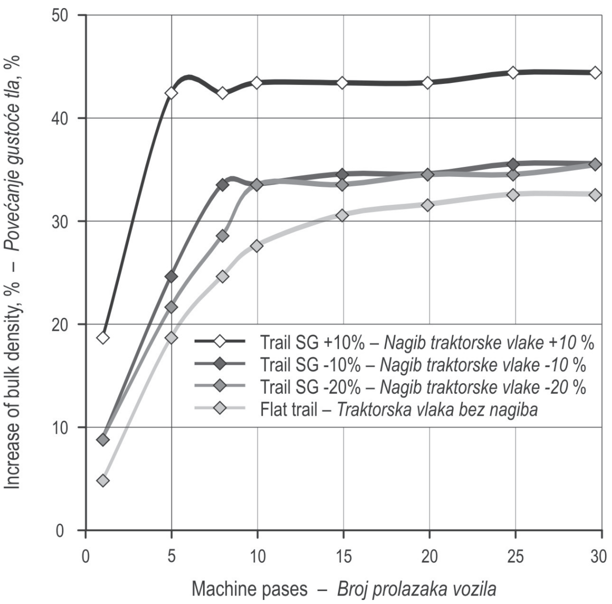

Fig. 6 Relationship between the increase of bulk density (%) and machine passes

Slika 6. *Odnos povećanja u gustoći tla (%) ovisno o prolasku vozila*

The independent samples t-test indicated that skidding had a statistically significant effect on the bulk density of soil on trails before and after machine passes in each trail with different slope gradients and by independent samples *t*-test and Duncan's test (b). The values are mean. Different letters within each slope treatment show significant differences ($P < 0.05$) (Fig. 5).

The results show that bulk density significantly increased as the number of machine passes increased (Fig. 6). Regardless of the slope gradient, the degree and level of compaction differed among trail slope using Duncan's multiple range test (Fig. 7 and Table 4). In Table 4, for each soil interval means are compared against each other after ANOVA using Duncan's test. Values are mean. The difference between values in a column followed by different superscripts is significant at $P < 0.05$.

In the other hand, generally, trails with four slopes show a similar trend of increasing soil bulk density with increasing amounts of machine passes. In flat trail, the bulk density in the top 0–10 cm of soil (1.06 g/cm^3) increased by 5% after 1 pass, 19% after 5 passes, 25% after 8 passes, 31% after 15 machine passes. In trail with a 10% slope or uphill skidding, the soil bulk density in-

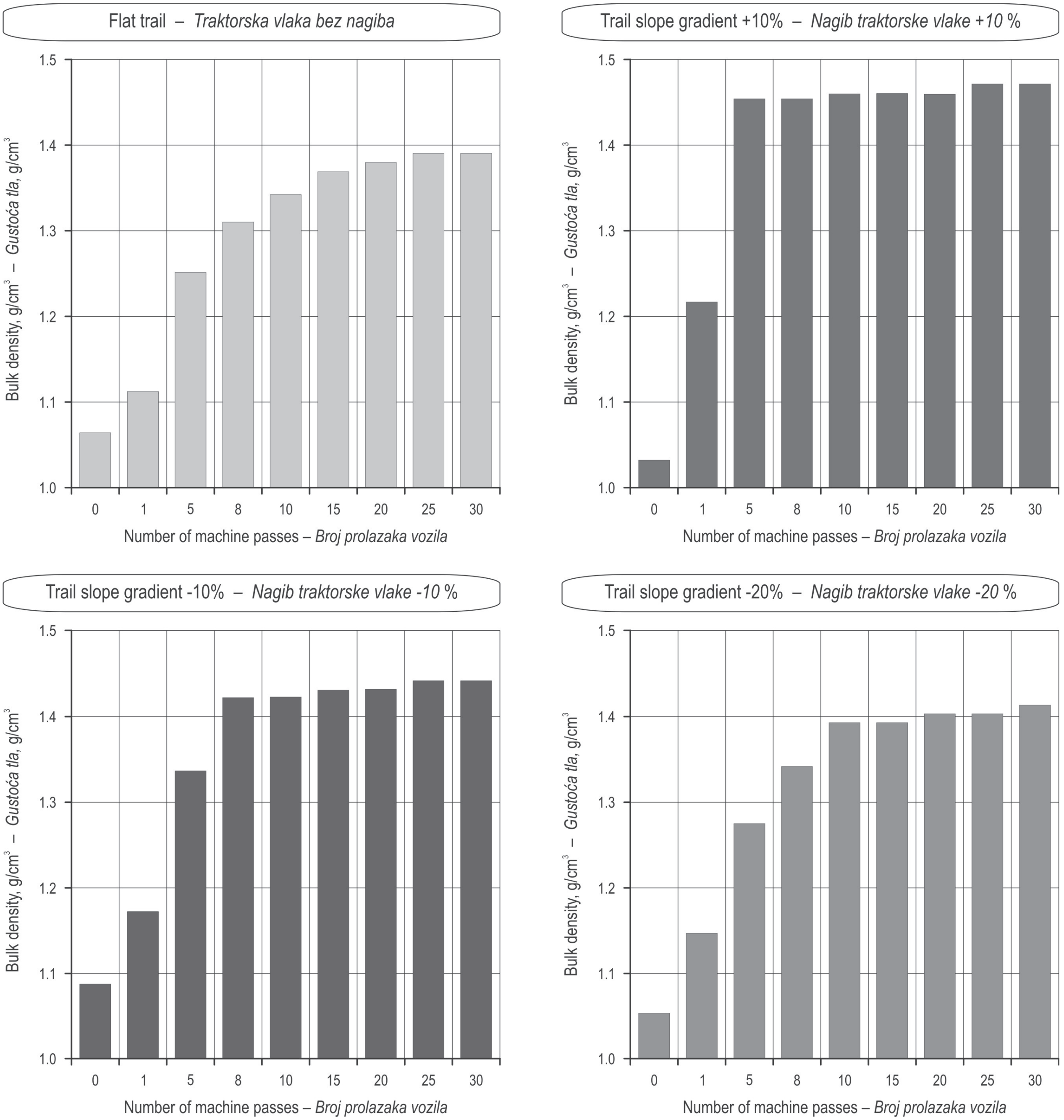

Fig. 7 Relationship between the increase of bulk density and machine passes on different slope gradients
Slika 7. *Odnos povećanja u gustoći tla s prolaskom vozila na vlakama različitih nagiba*

creased by 19% after 1 pass, 43% after 5 passes. Subsequent increase of the number of passes (up to 30 turns) did not increase the bulk density significantly. High level of increase in bulk density occurred after 5 machine passes and additional increase of passes did not increase the bulk density significantly. In the area with -10%, bulk density increased by 9% after 1 pass, 25% after 5 passes, 34% after 8 turns and in trail with -20% slope, by 9% after 1 pass, 22% after 5 passes, 29% after 8 turns and 34% after 10 passes. In flat trail, the highest rate of compaction, as bulk density increased, took place during the first 15 passes by 1.37 g/cm^3. In trail with 10% slope gradient, in contrast, high increase was observed in bulk density (1.44 g/cm^3) and it occurred

Table 4 Mean bulk density values (± standard deviation) as influenced by machine passes and slope gradient

Tablica 4. *Srednje vrijednosti gustoće tla (± vrijednost standardne devijacije) pod utjecajem prolazaka vozila i nagiba terena (SG)*

SG (%)	Number of machine passes – *Broj prolazaka vozila*								
	0	1	5	8	10	15	20	25	30
-10	$1.08 \pm 0.01^{a*}$	1.17 ± 0.01^{b}	1.33 ± 0.01^{b}	1.42 ± 0.02^{b}	1.42 ± 0.01^{b}	1.43 ± 0.01^{b}	1.43 ± 0.02^{b}	1.44 ± 0.02^{b}	1.44 ± 0.02^{b}
-20	1.05 ± 0.03^{ab}	1.14 ± 0.01^{c}	1.27 ± 0.02^{c}	1.34 ± 0.01^{c}	1.39 ± 0.03^{b}	1.39 ± 0.02^{c}	1.4 ± 0.01^{c}	1.4 ± 0.02^{c}	1.41 ± 0.01^{c}
0	1.06 ± 0.03^{ab}	1.11 ± 0.01^{d}	1.25 ± 0.02^{c}	1.31 ± 0.02^{c}	1.34 ± 0.02^{c}	1.37 ± 0.02^{c}	1.38 ± 0.01^{c}	1.39 ± 0.01^{c}	1.39 ± 0.01^{c}
10	1.03 ± 0.01^{b}	1.22 ± 0.01^{a}	1.46 ± 0.02^{a}	1.46 ± 0.02^{a}	1.47 ± 0.01^{a}	1.47 ± 0.03^{a}	1.47 ± 0.01^{a}	1.48 ± 0.01^{a}	1.48 ± 0.01^{a}

after 5 machine passes. Also, in downhill skidding with –10% and –20%, bulk densities were increased significantly after 8 and 10 machine passes, respectively. Then, soil bulk density for –10% and –20% was 1.41 and 1.41 g/cm^3, respectively. Bulk density in the 10% trail showed the highest value in comparison with other slope gradients of the trail (Fig. 5). Skidding operations along flat trail had the lowest compaction (Duncan's).

3.3 Soil compaction: influence of slopes and soil depths – *Zbijanje tla: utjecaj nagiba terena i dubine tla*

Table 5 shows the analyses of the soil bulk density data as influenced by position, slope gradient and depth after 20 machine passes. The results showed that position, depth, slope gradient, and the interaction effects of position × slope gradient and position × depth were all significant variables ($P<0.05$). General Linear Model (GLM) indicated two significant interaction terms, and namely position × slope gradient ($p<0.01$) and position × depth ($p<0.01$). It can be noticed that bulk density values of control sample points (no pass) in four slope gradients are clearly less than compacted values. The interaction between position and depth was also significant.

Average pre-harvest bulk densities for three soil depth classes, 0–10 cm, 10–20 cm, and 20–30 cm were 1.06 g/cm^3, 1.27 g/cm^3, and 1.42 g/cm^3, respectively. After 20 machine passes, bulk density increased in depth under the skid trails in all slope gradients of trails, but the major increase occurred in the top of the soil profile at 0–10 cm. In flat trail, bulk density increased by 30% in 0–10 cm depth, by 20% in 10–20 cm, and by 17.5% in 20–30 cm, after 20 machines passes. In trails with a 10% slope, the increase in bulk density for all depths was significantly higher as compared

Table 5 Analysis of variance (ANOVA) for the effect of sample position, slope gradient, and depth on bulk density in skid trials

Tablica 5. *Analiza varijance (ANOVA) podataka nagiba terena, dubine tla, gustoće tla i mjesta uzimanja uzoraka na traktorskim vlakama*

Source *Izvor podataka*	Sum of Square *Zbroj kvadrata*	df	Mean Square *Srednja kvadratna vrijednost*	*F*-value F *vrijednost*	*P*-value P *vrijednost*
Slope – *Nagib terena*	0.012	3	0.004	3.78	0.02
Position – *Položaj*	1.611	1	1.611	1528	0.00
Depth – *Dubina tla*	1.035	2	0.518	491	0.00
Slope * Position *Nagib terena * Položaj*	0.021	3	0.007	6.59	0.00
Slope * Depth *Nagib terena * Dubina tla*	0.003	6	0.001	0.48	0.82
Position * Depth *Položaj * Dubina tla*	0.046	2	0.023	21.7	0.00
Slope * Position * Depth *Nagib terena * Položaj * Dubina tla*	0.001	6	0.00	0.21	0.97

with those observed in trails with –10%, –20% slope, and flat trail. Fig. 8 shows how the relative change in bulk density varied with slope trail in soil depth. In trail with 10% slope, bulk density increased by 42% in 0–10 cm depth, by 28% in 10–20 cm, and by 20% in 20–30 cm, after 20 machine passes. The independent samples *t*-test indicated that skidding had a statistically significant effect on the soil bulk density on trails before and after vehicle passes in soil depth ($p<0.05$). Deeper in the soil profile, differences between control and the treatments in four slope gradient became smaller. The highest level of increase in bulk density was found in the trail with 10% slope gradient between control and the treatments.

For the soil bulk density samples in four slope gradient, one-way analysis of variance (ANOVA) and Duncan's test were used to see if there were significant differences ($P<0.05$) between the soil depths. In flat trail before and after skidding, bulk density increased significantly in all depths (Fig. 9), but there were no significant differences between soil depths at 10–20 cm and 20–30 cm in trails with uphill (10%) and downhill (–10% and –20%) slope gradient. With respect to the bulk density values for different trails, smaller values were generally observed compared with uphill and downhill skidding for flat trail. However, a peak can also be seen in the depth interval of 20–30 cm. Also, 10% trail resulted in the highest bulk density values for all depths, while flat trail showed the smallest degree of compaction.

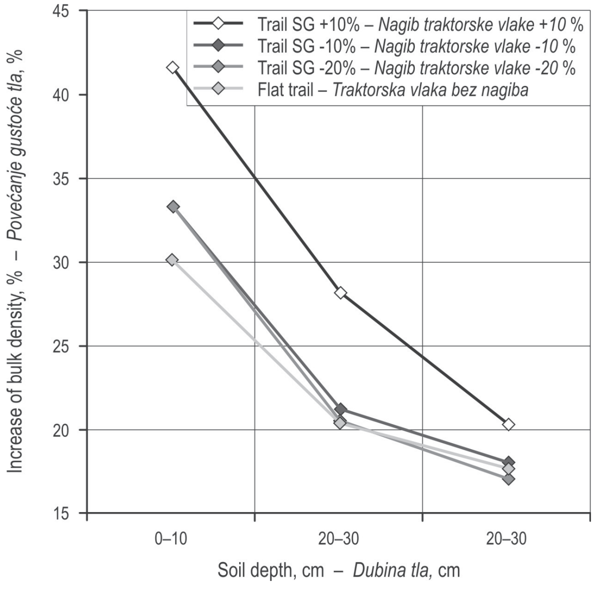

Fig. 8 Average decrease in bulk density with soil depth on skid trails of four slope gradients

Slika 8. *Prosječno smanjenje gustoće na različitoj dubini tla*

4. Discussion – *Rasprava*

4.1 Soil disturbance – *Oštećenje tla*

Once the sampling method was established, the soil disturbance survey was both quick and easy to complete. In this forest where skidding is common, the skid trail pattern is distributed unevenly because of terrain steepness. Using a different sampling method in this situation did not result in an exactly accurate survey and had many overestimations. Compared to other studies (Froehlich and McNabb 1984; Rab et al. 2005; Šušnjar et al. 2006), soil disturbance in this study occupied less than 8 percents. This agreed with Eliasson (2005) who found that soil disturbance will be affected by several factors such as wheel slip, vibration and number of vehicle passes.

4.2 Soil compaction: influence of slopes and machine passes – *Zbijanje tla: utjecaj nagiba terena i prolaska vozila*

The results show that the average bulk density significantly increased after the operation of rubber-tired skidders. However, in different slope gradient percentages, the increased bulk densities were statistically different. The results of most studies were consistent with our results (Sidle and Drlica 1981; Froehlich and McNabb 1984; Gayoso and Iroume 1991; Eliasson 2005; Šušnjar et al. 2006; Ampoorter et al. 2007; Eliasson and Wasterlund 2007; Horn et al. 2007; Jamshidi et al. 2008). Also, Horn et al. (2007) showed that each stress applied at the soil surface is always transmitted three-dimensionally and causes not only soil compaction but also shear effects.

The results show that bulk density significantly increased with the increase of vehicle passes. In general, trails with four slopes show a similar trend of increasing soil bulk density with the increasing number of vehicle passes. For most treatments, the highest rates of increase in bulk density were achieved in the first 5 to 15 vehicle passes. Beyond 15 vehicle passes, there was usually very little increase in bulk density (Matangaran and Kobayashi 1999). In the flat trail, the skidder operator used the whole width of the road instead of traveling in the same wheel tracks. Impacts of the frequency of vehicle passes on soil compaction showed similar results in many researches (Sidle and Drlica 1981; Gayoso and Iroume 1991; Ampoorter et al. 2007; Jamshidi et al. 2008). This agreed with Wang et al. (2007) and Horn et al. (2007) who both claimed that subsequent vehicle passes increased the soil compaction at a lesser extent until there is little or no more compaction associated with further vehicle passes.

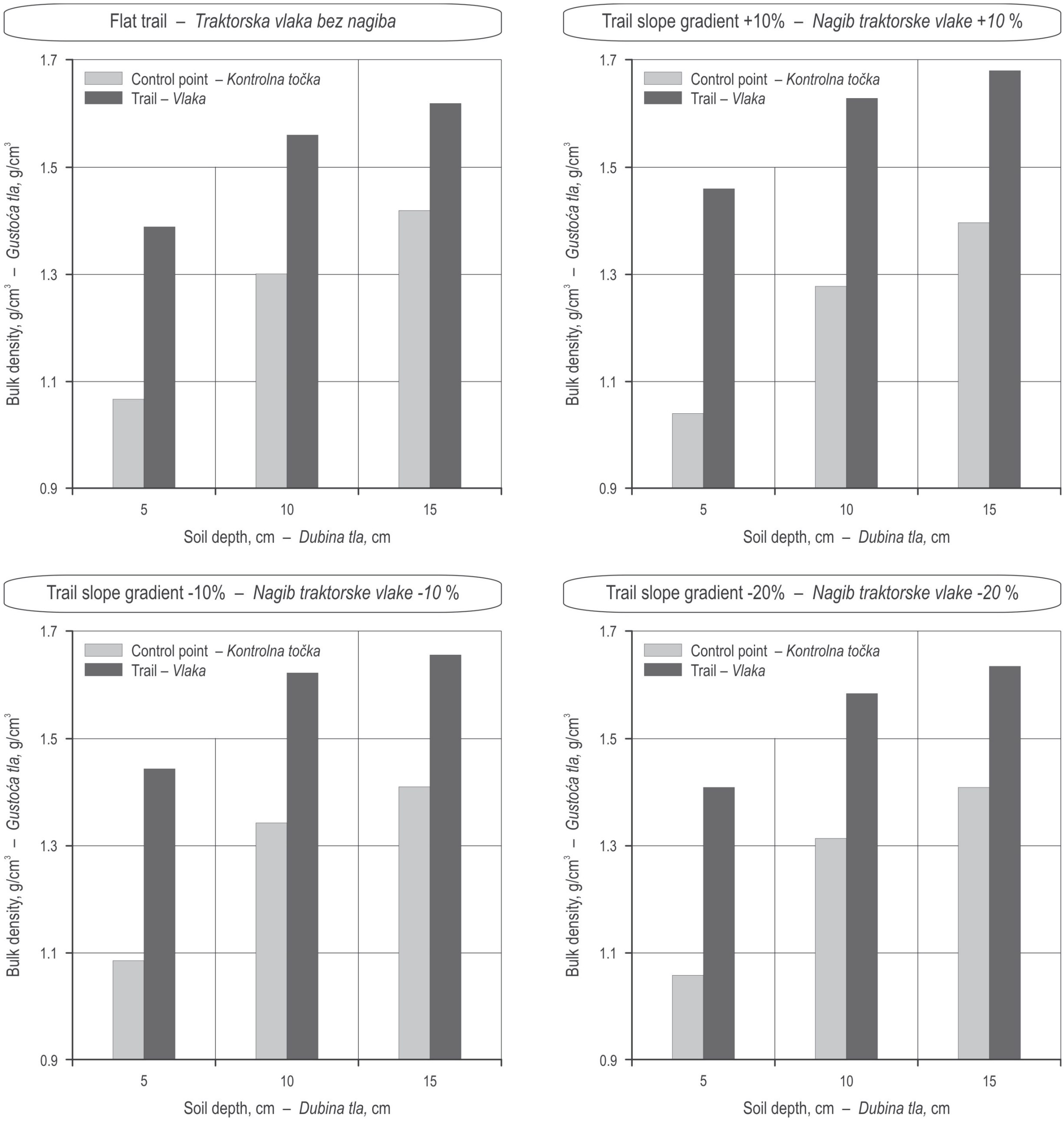

Fig. 9 Mean bulk density depending on different sampling places
Slika 9. *Srednje vrijednosti gustoće tla ovisno o mjestu uzimanja uzorka*

In this study, flat trails had the lowest bulk density, the trails with -10% and -20% slope gradient (downhill skidding) had intermediate bulk density and the trails with 10% slope gradient (uphill) had the highest compaction. This result can be explained based on the uneven load distribution between the downhill and uphill tires of the skidder (Jamshidi et al. 2008). Another reason for lower bulk density at the downslope track might be the dragging of the logs on or close to this track. Dragged behind the skidder, the logs and especially the log heads might have ripped and loosened up the surface of the highly compacted downslope wheel track (Jamshidi et al. 2008). However, Gayoso and Iroume (1991) stated that this may be a consequence of the problem that the skidder might face when logging in steep terrains. Under these conditions the vehicle slipped continuously and remained in a given place for a longer period of time, puddling and dragging the soil. In uphill skidding, rubber tires slipped on surface soil, then this wheel slippage, the vibration applied and shear strength caused the exposure of mineral subsoil, which has higher density than surface layer. Also, higher soil compaction in the uphill skidding can be explained by the higher load of the skidder rear axle. In the other hand, uphill skidding resulted in sever disturbance and compaction in initial vehicle pass, however bulk density in this condition had the highest amount in comparison to downhill skidding and flat skid trail. Also, Jamshidi et al. (2008) found that there was no detectable difference in compaction between vehicle skidding on flat trails and trails with longitudinal gradient or transversal slope. They concluded that the different site conditions and skidding frequencies might have affected the impacts of the different gradients/slopes.

4.3 Soil compaction: influence of slopes and soil depths – *Zbijanje tla: utjecaj nagiba terena i dubine tla*

The results showed that average pre-harvest bulk densities significantly increased as soil depth increased for all slope gradients. The wheel or track slip directly affected the soil structure and altered physical soil properties down to deeper depths. In the other hand, the values of the undisturbed soil bulk density mostly depends on the quantity of organic matter, and increasing soil depth; the organic matter rapidly decreases, and the bulk density increases in subsoil. In the upper soil, biological activity (roots and animals) can act to reduce resistance and soil bulk density while at lower depths soil texture, gravel content and structure may increase soil resistance and soil bulk density (Greacen and Sands 1980; Adams and Froehlich 1984; Froese 2004; Johnson et al. 2007). In this study, with increasing soil depth the compaction level also increased, which is in agreement with the results of other researchers (Greacen and Sands 1980; Sidle and Drlica 1981; Gent and Morris 1986; Gayoso and Iroume 1991; Ares et al. 2005; Eliasson and Wasterlund 2007; Johnson et al. 2007). The results show that deeper in the soil profile, differences between control and the treatments in four slope gradient became smaller. The highest level of increase in bulk density was found in the trail with 10% slope gradient (uphill) between control and the treatments. In flat trail, bulk density increased significantly in all depths. This is related to the rather homogeneous weight distribution of the skidder on flat skid trails. Compaction effect is most distinct in the upper 20 cm of the soil, since the exerted pressure is maximal at the soil surface and declines with increasing depth as the total pressure is spread out over an enlarging area. Thus, an increase generally occurs especially in the upper soil layers (Greacen and Sands 1980). It could also be suggested that the bearing capacity of the soil (maximum load without soil structure failure) grows with increasing bulk density. In this way the surface layer is protected against further compaction when traffic is continued (Ampoorter et al. 2007).

5. Conclusion – *Zaključak*

According to our findings, it may be concluded that the highest rate of compaction occurred after the initial few passes and reducing the number of trips made over the same trail had no effect in reducing soil compaction. In the other hand, subsequent vehicle passes will result in diminishing extra soil compaction. Hence, even one pass is already sufficient to induce a strong increase in bulk density. So, skidding operations should be limited to pre-planned skid trails, because vehicle traffic away from skid trails can significantly affect the increasing of the soil bulk density. The results of this research confirmed that preplanning of skid trails and directional felling will reduce ground disturbance. Slope gradient has a significant effect on soil compaction. Based on the results, it can be concluded that uphill slope gradients on trails should be as low as possible, particularly when vehicles are traveling loaded. The study showed that the skid trail slope and vehicle passes had a significant effect on soil compaction. Severe compaction of soil adversely affects the growth of plants by a combination of physical soil changes and plant physiological dysfunctions. Skidding operations should be planned when soil conditions are dry so as to minimize soil compaction, but if skidding must be done under wet conditions, the operations should be stopped when the vehicle traffic creates sever soil compaction. The distance between these trails must depend on the length of the felled tree and may range between 50 and 70 m distance in order to reduce the winching distance. The impact of felling of large trees is another source of compaction but this aspect has not been studied in this research.

Acknowledgements – *Zahvala*

This paper is one of the results of a research project that was carried out in the period 2010–2012 in the Hyrcanian forest in northern Iran. The authors would like to acknowledge the financial support of Iranian National Science Foundation (INSF) for the research project No. 88001084.

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Sažetak

Utjecaj broja prolazaka kotačnoga skidera na zbijanje tla

Upotreba je kotačnih skidera vrlo česta za privlačenje drva iz šume, ali pritom vozilo negativno utječe na okoliš. Cilj je istraživanja bio ispitati kako različiti nagibi terena (odnosno traktorskih vlaka), broj prolazaka vozila po traktorskoj vlaci i dubina tla utječu na zbijanje tla. Istraživano je zbijanje tla na četiri nagiba traktorskih vlaka: ravan teren, nagibi od +10 %, -10 %, -20 %; na tri različite dubine tla: 5, 15 i 25 cm te s obzirom na broj prolazaka vozla po vlaci: 0, 1, 5, 8, 10, 15, 20, 25 i 30 (slika 7). Uzorci su tla uzimani unutar traktorske vlake i izvan nje (slika 4) svakih 25 m duž vlake kako bi se vidio utjecaj natovarenoga vozila na tlo. Istraživanje je provedeno u Nastavno-pokusnom šumskom objektu Kheyrud, koji se nalazi unutar Hirkanijske šume u sjevernom Iranu, a drvo je privučeno skiderom Timberjack. Traktorske su vlake zauzimale 5,8 % ukupne površine istraživanoga područja (17 ha) uz dodatnih 0,8 % površine potrebne za pomoćno stovarište. S povećanjem broja prolazaka vozila povećala se i gustoća tla, ali je ipak najveće zbijanje tla ustanovljeno u prvih nekoliko prolazaka vozila. Privlačenje drva uzbrdo (+10 % nagiba terena) više je zbijalo tlo (slike 5 i 6) nego privlačenje drva nizbrdo (nagibi terena -10 % i -20 %). Povećanje je gustoće tla i na dubini od 20 do 30 cm bilo značajno (slika 8). Gustoća je tla na dubini od 5, 15 i 25 cm bila veća za 35, 22 i 17 % od gustoće tla na netaknutom tlu (slika 9). Kako bi se smanjilo zbijanje tla, potrebno je privlačiti drvo po unaprijed planiranim i za to predviđenim traktorskim vlakama te usmjereno obarati stabla kako bi se smanjilo kretanje vozila po šumskom bespuću jer već i nakon prvoga prolaska vozila dolazi do povećanja gustoće tla i njegova zbijanja. Također, privlačenje se drva treba odvijati u uvjetima suhoga tla kako bi se smanjila oštećenja na šumskom tlu.

Ključne riječi: zbijanje tla, gustoća tla, kotačni skider, Hirkanijske šume

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Received (*Primljeno*): February 12, 2012
Accepted (*Prihvaćeno*): Jaqnuary 11, 2013